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CLEANED COAL

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16. ABSTRACT

The chapter summarizes information on U.S. coal resources, describes physical coal cleaning technology, and discusses the potential for desulfurizing U.S. coals by physical techniques. It presents the costs of physical coal cleaning, summarizes the amounts of cleaned coals which can comply with different emission standards, and discusses the effects of coal sulfur variability on determining compliance coal properties. Finally, sample calculations are given for estimating the use of a given coal for compliance with various SO2 emission regulations. More than 460 physical coal cleaning plants in the U.S. can process over 400 million tons of raw coal per year. In 1979, about 344 million tons of coal was delivered to utilities from eight eastern and midwestern U.S. coal producing states. About 33 percent of this coal was cleaned. This cleaning reduced the potential annual SO2 emission from the combustion of these coals by over 1.7 million tons. While physical coal cleaning processes are principally designed for product standardization, increasing emphasis is being placed on cleaning for sulfur removal to aid in complying with emission standards. Emission limits for coal-fired boilers in the U.S. may range from less than 1.0 to more than 9.0 lb SO2/million Btu. Older boilers are generally subject to less stringent standards than new boilers.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Coal	Stationary Sources	08G,21D
Coal Preparation	Physical Coal Cleaning	09I
Desulfurization		07A,07D
Grinding Mills		13I
Washing		13H

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Table of Contents

	Page
Introduction and Summary	1
Coal Characteristics	4
Coal Rank	5
Coal Constituents	7
Potential for Constituent Removal	13
Coal Preparation Technology	23
Size Reduction	23
Size Classification	24
State-of-the-Art Cleaning Methods	24
Advanced Cleaning Techniques	33
Dewatering and Drying	37
Pollution Control/Waste Disposal	37
Status and Design of Commercial Plants	40
Level of Cleaning	40
Plant Design Trade-Offs	43
Plant Performance	45
Costs of Cleaning	52
Coal Cleaning for SO_2 Emission Reduction	76
Clean Air Act	77
SO_2 Emission Regulations	84
Potential Supply of Compliance Coals	85
Cleaning of Utility Coals	95
Cost Effectiveness	98
Sulfur Variability	103
Estimates of Performance	123
Table of Conversion Factors	130
References	131

FIGURES

No.		Page No.
19-1	Coal Fields of the United States (Coal Rank Not Distinguished in Alaska)	6
19-2	Cumulative Washability Data for Pittsburgh Coal Bed, Harrison County, Ohio	18
19-3	The Effect of Crushing Top Size and Specific Gravity of Separation on the Reduction of Ash, Pyritic Sulfur, Total Sulfur, and lb $SO_2/10^6$ Btu	20
19-4	McNally Mogul Washer. Source, McNally Pittsburgh, Inc.	26
19-5	Concentrating Table - Top View	28
19-6	McNally Lo-Flo Dense Media Vessel. Source, McNally Pittsburgh, Inc.	30
19-7	Froth Flotation Cell	32
19-8	Level 4 Coal Preparation Plant Flow Diagram	42
19-9	Comparison of PCC-1 & 2 Computer Model Results with Coal Preparation Plant Performance	51
19-10	Projected 1985 Coal Production in Ohio Able to Meet Various Emission Limits (Total Projected 1985 Coal Production = 1.34 Quads)	86
19-11	Projected 1985 Coal Production in Southern West Virginia Able to Meet Various Emission Limits (Total Projected 1985 Coal Production = 2.42 Quads)	88
19-12	Percentage of Projected 1985 Ohio Coal Production Able to Meet Various SO_2 Emission Standards Defined by an Emission Ceiling and Percentage SO_2 Reduction Using Physical Coal Cleaning at 1-1/2 in., 1.6 sp. gr.	92
19-13	Percentage of Projected 1985 Southern West Virginia Coal Production Able to Meet Various SO_2 Emission Standards Defined by an Emission Ceiling and Percentage SO_2 Reduction Using Physical Coal Cleaning at 1-1/2 in., 1.6 sp. gr.	93

FIGURES (Continued)

No.		Page No.
19-14	Kitt Mine Coal Preparation Plant - Hourly Incremental Data for Sulfur Dioxide Emission Parameter	105
19-15	Effect of Autocorrelation and Number of Reference Lots on $\hat{RSD}_n/\hat{RSD}_1$	116

TABLES

No.		Page No.
19-1	Coal Properties in Coal Washability Data Base - State and Regional Summary	12
19-2	Cumulative Washability Data for Pittsburgh Coal Bed, Harrison County, Ohio	16
19-3	Summary of Average Physical Desulfurization Potential of Coals by Region	22
19-4	Coal Preparation Plant Feed and Product Data	46
19-5	Comparison of Plant and Laboratory Washability Emission Parameters (lb $SO_2/10^6$ Btu)	48
19-6	Coal Preparation Plant Costs for Five Coals When Prepared at Levels 1, 2, and 4	54
19-7	Summary of Raw and Cleaned Coal Properties for Five Coals When Prepared at Levels 1, 2, and 4	55
19-8	Comparison of Power Generation Cost Components as a Function of Level of Cleaning	69
19-9	Relative Unit Power Generation Cost Components in $/ton of Level 1 Coal	72
19-10	Coal Cleaning Cost Savings for Case B	73
19-11	Change in Relative Percentage of Potential Cost Savings with Coal and Power Plant Site Factors	75
19-12	Range of SIP SO_2 Emission Limits for Coal-Fired Boilers in Selected States	79
19-13	Percentage of Projected 1985 Coal Production Able to Meet Selected Emission Limits Using Raw Coal or Cleaned Coal	90
19-14	Current (1979) SO_2 and Potential Reduction by Cleaning Utility Coal from Eight States	96
19-15	Potential SO_2 Emission Reductions and Costs Due to Selective Cleaning of Ohio and Southern West Virginia Coals Delivered to Utilities in 1979	102

TABLES (Continued)

No.		Page No.
19-16	Effect of Coal Statistical Parameters on Fractional Coal Emission Parameter	117

INTRODUCTION AND SUMMARY

Physical coal cleaning can be used to reduce the ash and sulfur content of coal and hence the potential sulfur dioxide (SO_2) emission which results from coal combustion. This chapter summarizes information on U.S. coal resources, describes physical coal cleaning technology, and discusses the potential for desulfurizing U.S. coals by physical techniques. It summarizes the amounts of cleaned coals which can comply with different emission standards and presents estimates of the cost of cleaning. It also discusses the characteristic variability in the sulfur content of coal and provides a method for estimating the mean coal sulfur value which will provide an expectation that a coal can comply with a specified emission regulation. Finally, sample calculations are given to illustrate some uses of coal washability and sulfur variability data.

Sulfur in coal is found in two major forms: organic and pyritic. Organic sulfur is chemically bonded to the carbon molecules of the coal and can only be removed if the bonds are broken by chemical processes. Pyritic sulfur, a mineral, occurs in discrete particles throughout the coal structure. In U.S. coals, the pyritic sulfur may comprise from 30 to 70 percent of the total sulfur content. Pyritic sulfur can be removed by physical methods.

Coal is physically cleaned--a process sometimes called washing--by crushing it to a point where some of the mineral impurities are released from the coal structure. The mineral and coal particles can then be separated by techniques which rely on differences in density or surface properties. The degree of desulfurization obtained by crushing and specific gravity separation depends on the sulfur level in the raw coal, type of sulfur, and the coal preparation techniques used. Commercial coal cleaning plants are capable of reducing the potential SO_2 emissions from coal combustion by 10 to 50 percent, depending upon the coal and process employed.

In 1979, there were more than 460 physical coal cleaning plants in the U.S. They were capable of processing over 400 million tons (363 million Mg) of raw coal per year. In 1979, approximately 344 million tons (312 million Mg) of coal was delivered to utilities from eight eastern and midwestern U.S. coal producing states. Approximately 33 percent of this coal was cleaned. It is estimated that these cleaning activities reduced the potential annual SO_2 emission from the combustion of these coals by over 1.7 million tons (1.5 million Mg). While physical coal cleaning processes are principally designed for product standardization, increasing emphasis is being placed on cleaning for sulfur removal to aid in complying with SO_2 emission standards.

Emission limits for coal fired boilers in the U.S. may range from less than 1.0 lb $SO_2/10^6$ Btu (430 ng/J) to greater than 9.0 lb $SO_2/10^6$ Btu (3869 ng/J). Older boilers are generally subject to less stringent standards than new boilers. Low sulfur coals and physically cleaned coals can be used to comply with many emission regulations which incorporate moderate emission limits. New boilers require the use of best available pollution control technology. Some standards for new sources require a 70 to 90 percent reduction in the potential SO_2 emissions as related to the raw coal. Conventional physical coal cleaning by itself cannot be used as a technique to comply with these standards. However, in some instances combinations of physical coal cleaning and flue gas desulfurization (FGD) may be the most cost effective method for complying with these emission regulations.

This chapter summarizes a wide range of information on U.S. coals, coal cleaning, and SO_2 emission regulations from coal combustion. The treatment of these topics has been greatly summarized and simplified.

Both English units and Standard International (SI) units of measure are used in the text. For simplification, figures and tables are expressed solely in English units. A table with English to SI unit conversions is provided at the end of this chapter.

COAL CHARACTERISTICS

Coal is a complex assemblage of materials which originate from peat and detrital material deposited in swamps or bogs. In addition to its plant-derived organic constituents (carbon, hydrogen, oxygen, and nitrogen), coal contains significant quantities of minerals and inorganic elements. The relative abundance of the organic and inorganic constituents varies significantly between coals of different types and between different locations in a single coal seam. The variability of coal properties is a function of:

- The chemical composition and structure of the coal forming vegetal matter,
- The chemical changes which occurred during the accumulation and burial of the coal forming matter,
- The deposition of inert sediments during accumulation,
- The characteristics of the sedimentary rock above and below the coal seam, and
- The subsequent geologic history of the deposit such as the permeation of ground water and the depth of burial.

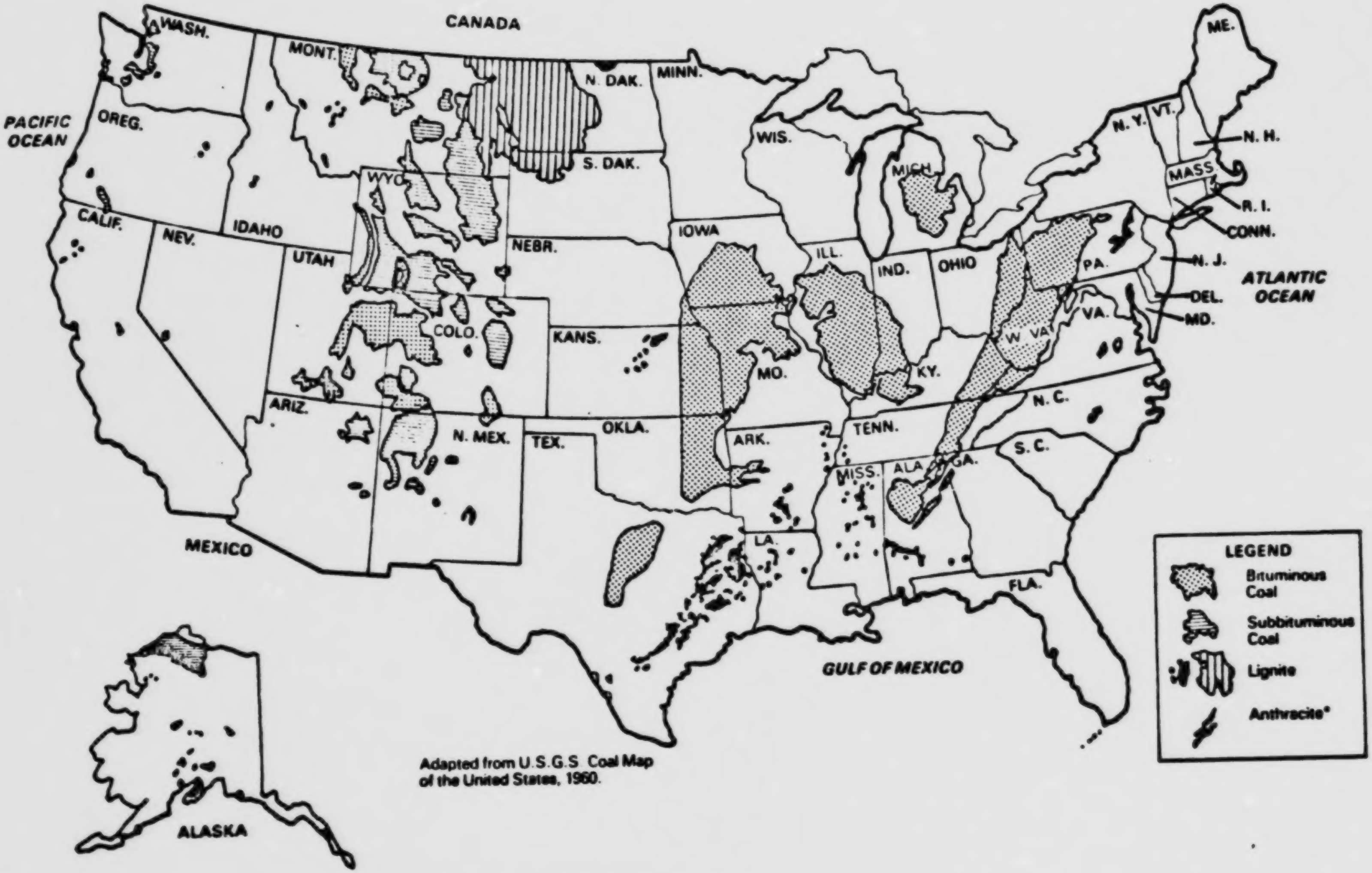
A number of different systems are used to classify and characterize coal. Some systems depend on the gross physical and chemical properties which are related to the use for which coal is intended--combustion, coke making, or synthetic fuels. Other systems are based on the macroscopic or microscopic constituents of which the whole coal is composed.

Coal Rank

The classification of coal by rank provides information useful in assessing its properties as a fuel. Rank is related to the degree of coalification--the process of deposition, burial, and metamorphosis. Age, volatile matter, fixed carbon, bed moisture, and oxygen are indicative of rank, but no one item completely defines it. The American Society for Testing and Materials (ASTM) classification system includes four classes of coals: anthracite, bituminous, subbituminous, and lignite (1). Each class is in turn divided into groups. For the higher ranked coals, the ordering is based upon the fixed carbon and volatile matter content. Fixed carbon increases and volatile matter decreases with increasing rank for these coals. Lower ranked coals are ordered in terms of their calorific value as determined on a moist mineral matter free basis: the heating value decreases with decreasing rank.

The location of coal fields and the rank of coals in these fields are shown in Figure 19-1. Anthracite is found mainly in Pennsylvania, with small deposits in Virginia, Arkansas, Colorado, and New Mexico. It is used primarily for home heating and for fuel in small commercial and industrial boilers. The total amount of anthracite in the demonstrated reserve base of the U.S. is estimated to be 7.3 billion tons (6.6 billion Mg) (2).

Bituminous coals are found in almost every coal producing state. However, they predominate in the eastern and midwestern coal states. Bituminous coals are used mainly for electrical production, coke


CANADA
PACIFIC OCEAN
ATLANTIC OCEAN
GULF OF MEXICO
MEXICO
WASH.
OREG.
CALIF.
NEV.
IDAHO
MONT.
WYO.
UTAH
ARIZ.
COLO.
N. MEX.
N. DAK.
S. DAK.
NEBR.
KANS.
OKLA.
TEX.
MINN.
IOWA
MO.
ARK.
LA.
WIS.
ILL.
MICH.
IND.
OHIO
KY.
TENN.
MISS.
ALA.
GA.
FLA.
S. C.
N. C.
VA.
W. VA.
PA.
N. Y.
VT.
N. H.
ME.
MASS.
R. I.
CONN.
N. J.
DEL.
MD.
ALASKA
LEGEND
Bituminous Coal
Subbituminous Coal
Lignite
Anthracite*

Adapted from U.S.G.S. Coal Map of the United States, 1960.

*Principal deposits in Pennsylvania; small deposits in Arkansas, Colorado, New Mexico, and Virginia. Anthracite - meta-anthracite deposits in Massachusetts and Rhode Island

Figure 19-1. Coal Fields of the United States
(Coal Rank Not Distinguished in Alaska)

production, and small boiler fuels. There are more than 241.9 billion tons (219 billion Mg) of bituminous coals in the demonstrated reserve base (2). Most of the coal which is cleaned in the U.S. is bituminous.

Subbituminous coals are found mainly in Montana, Wyoming, Alaska, Colorado, New Mexico, and Washington. There are more than 182.4 billion tons (165 billion Mg) of these coals in the demonstrated reserve base (2). They are used primarily as boiler fuels.

There are more than 42.9 billion tons (38.9 billion Mg) of lignitic coals in the demonstrated reserve base (2). The largest reserves are found in Montana, North Dakota, Texas, Alaska, and Alabama. In the past these coals were not widely used because of their low heating value and the distance of most lignite reserves from major industrial centers. Recently, mine mouth power plants have been constructed in North Dakota and Texas to utilize these resources.

Coal Constituents

Coals contain a wide variety of organic and mineralogical constituents. In the same way that inorganic rocks are composed of minerals--for example granite is made up of feldspar, quartz, and mica--the organic coal structure consists of identifiable components called macerals. But there is a difference. Whereas a mineral is characterized by a fairly well-defined chemical composition, by the uniformity of its substance, and by the fact that most minerals are crystalline, coal macerals vary widely in chemical composition and physical properties (3).

Although microscopic examinations show these distinct maceral types to be more or less homogenous, they often contain a large number of small mineral inclusions. Systems which are used to classify the organic microlithotypes in coal are described in Reference 3.

Organically Related Constituents. Organic sulfur is believed to exist in the form of several functional groups: thiophenes, aryl sulfides, cyclic sulfides, aliphatic sulfides, disulfides, and mercaptans (thiols) (4). The total organic sulfur content in bituminous coals consists primarily of thiophenes (40 to 70 percent of total). The rest is believed to consist of aryl sulfides, cyclic sulfides, and aliphatic sulfides. Disulfides and mercaptans are not believed to contribute significantly to the organic sulfur content in bituminous coal. They may be present in lignites in larger proportions (4).

Nitrogen in coal is believed to be associated primarily with aromatic ring structures in the form of pyridine, picoline, quinoline, and nicotine (5).

Trace elements commonly associated with the organic structure of coal include: germanium, beryllium, boron, antimony, cobalt, nickel, copper, chromium, and selenium (6).

Inorganically Related Constituents. In addition to purely organic substance, coal contains varying amounts of inorganic components:

minerals and trace elements. These inorganic components are classified into three groups according to their origin (3):

(1) Inorganic matter from the original plants,

(2) Inorganic/organic complexes and minerals which formed during the first phase of the coalification process or which were introduced by wind or water into the coal deposits as they were forming, and

(3) Minerals deposited during the second phase of the coalification process, after consolidation of the coal, by ascending or descending solutions in cracks, fissures, or cavities or by the alteration of primarily deposited minerals.

Minerals and elements associated with the original organic matter and the first phase of coalification are fine-grained and intimately interspersed in the coal. This inorganic material is often called "inherent" minerals. By contrast, the minerals which formed during the second stage of the coalification process are large grained and distinct from the coal organic structure, because most of them were deposited in cracks and fissures (3). These minerals are often called "extraneous" minerals. Extraneous minerals can be removed by conventional physical coal cleaning techniques; inherent minerals cannot.

There is generally not a strong correlation between coal rank and the quantity and characteristics of the coal mineral matter. The mineral content of coal is generally a function of the depositional environment, the subsequent exposure of sediments, and the presence of mineralized ground or surface water. Coal rank and degree of metamorphosis are mainly functions of the temperature, pressure, and time of coalification.

Minerals associated with coal include clays, iron disulfides, carbonates, oxides, hydroxides, sulfides, phosphates, sulfates, silicates, and salts. Clays are by far the most important coal minerals. They generally account for 60 to 80 percent of the coal mineral content. Carbonates are the next most common, followed by iron disulfides, oxides, hydroxides, and salts.

Trace elements which are normally associated with the inorganic structure of coal include: zinc, cadmium, manganese, arsenic, molybdenum, and iron. A number of metals (including cobalt, nickel, copper, chromium, and selenium) are often associated with both the inorganic and the organic constituents of coal. In some instances, they are probably associated with sulfide minerals in coal. In other cases, they may be associated with organometallic compounds as chelated species, or as absorbed cations (6).

Relationship of Mineral Matter to Ash. An evaluation of the mineral content of coal is a difficult and costly process. For this reason the coal ash content is used as a surrogate for quantifying the mineral content of coal. Whole coal samples are burned in a laboratory combustor, converting the minerals and inorganic elements to ash. The weight of this ash approximates the original mineral content of the coal.

The Sulfur and Ash Content of U.S. Coals. The sulfur and ash content of coal varies from coal field to coal field and from seam to seam within the same coal field. It also varies from location to location within a single mine and between different elevations at the same location.

The average ash content, calorific content, and total sulfur content, for U.S. coals are summarized in Table 19-1 (7). The data are presented for six coal regions and the states within those regions. These data are from a computerized data base developed by the Department of Energy on the desulfurization potential of U.S. coals.

The sulfur and ash content of Northern Appalachia, eastern Midwestern, and western Midwestern region coals is higher than the sulfur and ash content of the Southern Appalachian, Alabama, and Western coals. This is also reflected in the potential sulfur emissions which would result from the combustion of these coals. The relative difference between the sulfur and ash content of the various coal basins results primarily from differences in the depositional environments which controlled initial stages of coalification in the ancient peat swamps. Differences within a coal mine or bed may have resulted from localized differences in the depositional environment or from differences in the subsequent coalification process.

Table 19-1. Coal Properties in Coal Washability Data Base - State and Regional Summary(7)

Region[(a)]	State	Number of Samples	Heating Value (Btu/lb)				Total Sulfur (%)				Ash (%)			
			Min.	Max.	Mean	Std. Dev.	Min.	Max.	Mean	Std. Dev.	Min.	Max.	Mean	Std. Dev.
1	MD	35	11,026	14,244	12,661	797	0.71	6.13	2.58	1.26	8.0	26.90	16.41	4.36
	OH	90	8,571	14,256	12,494	930	0.67	6.55	3.55	1.39	3.57	37.43	13.61	5.56
	PA	170	7,070	14,658	12,982	1,057	0.53	9.40	2.56	1.56	4.80	51.9	14.41	6.60
	WV-N	30	9,186	13,973	12,647	1,266	1.06	6.33	3.06	1.21	6.63	37.53	15.74	8.21
	Total*	325	7,070	14,658	12,781	1,038	0.53	9.40	2.88	1.51	3.57	51.90	14.53	6.32
2	GA	0	0	0	0	0	0	0	0	0	0	0	0	0
	KY-E	13	11,120	14,366	12,986	1,163	0.56	4.08	1.44	1.21	2.13	23.47	11.48	7.44
	NC	0	0	0	0	0	0	0	0	0	0	0	0	0
	TN	8	12,966	14,321	13,672	404	0.66	3.61	1.17	0.99	3.00	12.87	7.90	3.56
	VA	8	11,872	14,828	13,715	1,143	0.48	1.17	0.77	0.23	1.97	22.77	10.04	7.83
	WV-S	16	11,000	14,210	13,064	901	0.59	1.90	0.90	0.35	5.30	26.07	12.73	5.84
	Total*	45	11,000	14,828	13,266	998	0.48	4.88	1.08	0.82	1.97	26.07	11.03	6.45
3	AL	10	12,765	15,056	13,696	914	0.59	3.76	1.33	0.95	1.73	16.27	9.50	6.38
	Total*	10	12,765	15,056	13,696	914	0.59	3.76	1.33	0.95	1.73	16.27	9.50	6.38
4	IL	40	10,777	13,294	11,944	683	1.14	7.82	3.86	1.39	7.63	25.03	15.29	4.45
	IN	21	11,596	13,452	12,546	531	0.67	7.17	3.67	1.54	6.37	19.57	11.89	3.46
	KY-W	37	8,698	13,676	12,339	864	2.17	5.02	4.05	0.71	5.17	37.63	13.81	5.52
	MI	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total*	98	8,698	13,676	12,222	763	0.67	7.82	3.89	1.21	5.17	37.63	14.00	4.84
5	AR	3	13,900	14,293	14,123	202	1.81	3.96	3.12	1.15	7.10	8.97	8.27	1.02
	IA	17	10,165	13,230	11,601	759	2.53	12.11	6.76	2.49	7.00	26.87	16.15	4.67
	KS	8	9,550	12,857	11,544	1,212	4.02	6.65	5.04	1.03	13.40	34.50	21.48	7.79
	MO	9	9,708	12,914	11,665	934	4.22	6.16	4.97	0.64	11.60	29.57	19.04	5.06
	OK	7	12,156	14,934	13,461	923	0.57	6.00	3.10	2.33	3.97	20.20	10.09	5.68
	TX	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total*	44	9,550	14,934	12,072	1,232	0.57	12.11	5.25	2.32	3.97	34.50	16.21	6.68
6	AZ	6	12,197	12,649	12,348	162	0.47	0.68	0.56	0.08	6.37	9.33	8.36	1.11
	CO	19	11,311	13,839	12,449	796	0.27	1.04	0.58	0.36	3.53	18.87	9.68	4.01
	MT	9	11,417	12,288	11,749	277	0.74	1.75	1.00	0.37	7.37	10.43	8.83	0.98
	NM	11	10,577	13,675	11,815	1,167	0.48	0.76	0.64	0.10	4.50	22.17	14.96	6.49
	ND	1	11,007	11,007	11,007	0	1.18	1.18	1.18	0	8.87	8.87	8.87	0
	OR	0	0	0	0	0	0	0	0	0	0	0	0	0
	SD	0	0	0	0	0	0	0	0	0	0	0	0	0
	UT	9	12,598	13,778	13,217	383	0.40	0.67	0.52	0.10	4.33	10.37	7.09	2.10
	WA	0	0	0	0	0	0	0	0	0	0	0	0	0
	WY	10	9,947	12,733	11,676	1,056	0.55	1.31	0.88	0.29	2.23	15.90	7.40	4.62
	Total*	65	9,947	13,839	12,201	929	0.27	1.84	0.70	0.32	2.23	22.17	9.63	4.65
TOTAL U.S.*		587	7,070	15,056	12,623	1,059	0.27	12.11	2.82	1.84	1.73	51.90	13.57	6.24

* Due to independent rounding, data may not add to totals.

(a) 1 - Northern Appalachian, 2 - Southern Appalachian, 3 - Alabama, 4 - Eastern Midwestern, 5 - Western Midwestern, 6 - Western.

The Potential for Constituent Removal

Constituents can be removed from coal by either physical or chemical techniques. In most commercial physical cleaning processes, coal and mineral particles are separated by techniques which rely upon differences in their size, shape, and specific gravity or their surface properties. Those that rely on specific gravity separation techniques predominate. The amount of constituents which can be removed by a given technique or process changes from coal to coal. The potential for constituent removal or cleanability can be considered to be an inherent property of each coal--a property determined by the relative amount and size distribution of the macerals and minerals of which the whole coal is composed.

Most of the published data on the cleanability of different coals are based on specific gravity separation techniques. No systematic collection of data on other techniques has been published.

Specific Gravity and Size Designations. Coal and mineral particles are often characterized according to their size and density. It is common practice to specify their density relative to water; i.e., their specific gravity. Thus a particle with a specific gravity of 1.0 would have a density of 62.4 lb/ft^3 (1.0 g/cm^3), and a particle with a specific gravity of 2.0 would have a density of 124.8 lb/ft^3 (2.0 g/cm^3).

Large particles are generally specified by their maximum mean diameter in inches or millimeters. Small particles are generally specified by their Tyler mesh size. The Tyler mesh size is the number of screen openings per inch in a standard square screen sieve. The maximum size or top size of a 14 mesh particle is the largest particle size that will pass through the 0.0469 inch (1.2 mm)[a] opening. All particles smaller than 0.0469 inch (1.2 mm) will also pass through the 14 mesh screen. This size range of particles is denoted as 14 x 0 mesh. In a similar fashion the size range of particles that will pass through a 14 mesh screen but which will be retained on a 100 mesh screen (0.0059 inch or 0.150 mm screen opening) is denoted by 14 x 100 mesh. In the text of this chapter the Tyler mesh size will be followed by the screen opening in millimeters; for example, 14 x 100 mesh (1.2 x 0.15 mm).

Washability. Pyrite, the most common iron disulfide (FeS_2), may constitute from less than 1 to more than 7 percent of the coal weight. It has a specific gravity of 5.0. The specific gravity of other coal minerals ranges from approximately 1.9 to 2.2, and the specific gravity of coal macerals ranges from 1.2 to 1.7.

The potential for reducing the mineral and sulfur content of a coal by specific gravity separations can be determined by laboratory tests called float-sink tests or washability tests (8). In these tests, a coal sample is crushed and separated into various size ranges. Each size fraction is float-sink tested in organic liquids of standardized specific gravity. The weight, percent ash, heat content, total sulfur, and pyritic sulfur content of each density and size fraction are then determined. This matrix of data characterizes the washability of a given coal. It is used to determine the mineral and desulfurization potential and specify the design and operating conditions for physical coal preparation equipment.

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[a] English and metric equivalents for particle screen size are from: Testing Sieves and Their Uses, Handbook 53, 1976 Edition, CE Tyler Industrial Products.

Float-Sink Data. The effects of crushing and specific gravity of separation are "qualitatively" similar for nearly all coals. The weight recovery (yield), energy recovery, ash content, and sulfur content decrease with decreasing specific gravity of separation. At low specific gravities, only those particles which are relatively free of embedded pyrite or mineral particles will float. Coal particles containing moderate amounts of mineral and pyrite particles sink along with pure mineral particles. This produces a cleaner product but at the expense of high energy losses to the sink or refuse fraction.

Crushing the coal to finer particle sizes liberates a higher fraction of the mineral and pyrite particles from the organic coal structure. This results in improved separation of the mineral and organic components during the subsequent float-sink tests.

Washability data from a coal face sample taken from the Pittsburgh coal bed in Harrison County, Ohio, are shown in Table 19-2 (8). These data are for three representative subsamples which have been crushed to pass through screen openings of 1-1/2 inch (37.5 mm), 3/8-inch (9.5 mm), and 14 mesh (1.2 mm). Each subsample was again fractionated by float-sink separations at specific gravities of 1.3, 1.4, 1.6, and 1.9.

Table 19-2. Cumulative Washability Data for Pittsburgh Coal Bed, Harrison County, Ohio[a]

SAMPLE CRUSHED TO PASS 1-1/2 INCHES

PRODUCT	RECOVERY,%		BTU/LB	ASH,%	SULFUR,%		LB SO2/M BTU
	WEIGHT	BTU			PYRITIC	TOTAL	
FLOAT-1.30	35.4	39.2	13925	3.7	.40	1.73	2.5
FLOAT-1.40	73.8	79.7	13592	6.0	1.01	2.47	3.6
FLOAT-1.60	90.3	96.0	13375	7.5	1.43	2.98	4.5
FLOAT-1.90	93.2	98.0	13231	8.5	1.56	3.12	4.7
TOTAL	100.0	100.0	12580	13.0	2.01	3.48	5.5

SAMPLE CRUSHED TO PASS 3/8 INCH

PRODUCT	RECOVERY,%		BTU/LB	ASH,%	SULFUR,%		LB SO2/M BTU
	WEIGHT	BTU			PYRITIC	TOTAL	
FLOAT-1.30	52.5	57.8	13939	3.6	.32	1.71	2.5
FLOAT-1.40	81.2	88.1	13722	5.1	.74	2.21	3.2
FLOAT-1.60	88.9	95.1	13534	6.4	.94	2.44	3.6
FLOAT-1.90	92.4	97.7	13375	7.5	1.11	2.62	3.9
TOTAL	100.0	100.0	12652	12.5	1.89	3.35	5.3

SAMPLE CRUSHED TO PASS 14 MESH

PRODUCT	RECOVERY,%		BTU/LB	ASH,%	SULFUR,%		LB SO2/M BTU
	WEIGHT	BTU			PYRITIC	TOTAL	
FLOAT-1.30	23.3	26.1	14084	2.6	.23	1.61	2.3
FLOAT-1.40	78.6	85.9	13751	4.9	.56	1.99	2.9
FLOAT-1.60	87.3	93.9	13534	6.4	.77	2.21	3.3
FLOAT-1.90	91.5	97.1	13346	7.7	.98	2.42	3.6
TOTAL	100.0	100.0	12580	13.0	2.00	3.48	5.5

[a] All values given on a moisture-free basis. The air dried raw coal moisture content of the original sample was 2.6 percent. Data from Ref. 8.

The data in Table 19-2 show that, by crushing the sample to 1-1/2 inch (37.5 mm) top size and by taking a float product at I.6 s.g., 90.3 percent by weight of the sample would be recovered. This float product would have a moisture-free heating value of 13,375 Btu/lb (31,110 J/g), an ash content of 7.5 percent, a pyritic sulfur content of 1.43 percent, and a total sulfur content of 2.98 percent. Although 90.3 percent of the weight content of the original sample was recovered, 96.0 percent of its original energy content was recovered. Upon combustion this sample would have emitted 4.5 lb $SO_2/10^6$ Btu (1935 ng SO_2/J).

In a similar fashion data from Table 19-2 can be used to determine the properties which can be obtained by washing the sample at four different specific gravities after crushing to any of three different top sizes. Data for the raw coal samples are given in the rows designated as total.

The effect which the specific gravity of separation has upon the 3/8-inch (9.5 mm) float product of the Harrison County coal is presented graphically in Figure 19-2. The weight recovery, Btu recovery, ash content, sulfur content, and SO_2 emission parameter (lb $SO_2/10^6$ Btu) all decrease with decreasing specific gravity of separation. Only the heating value increases. This increase is a consequence of the reduced ash content of the coal at low separation gravities.

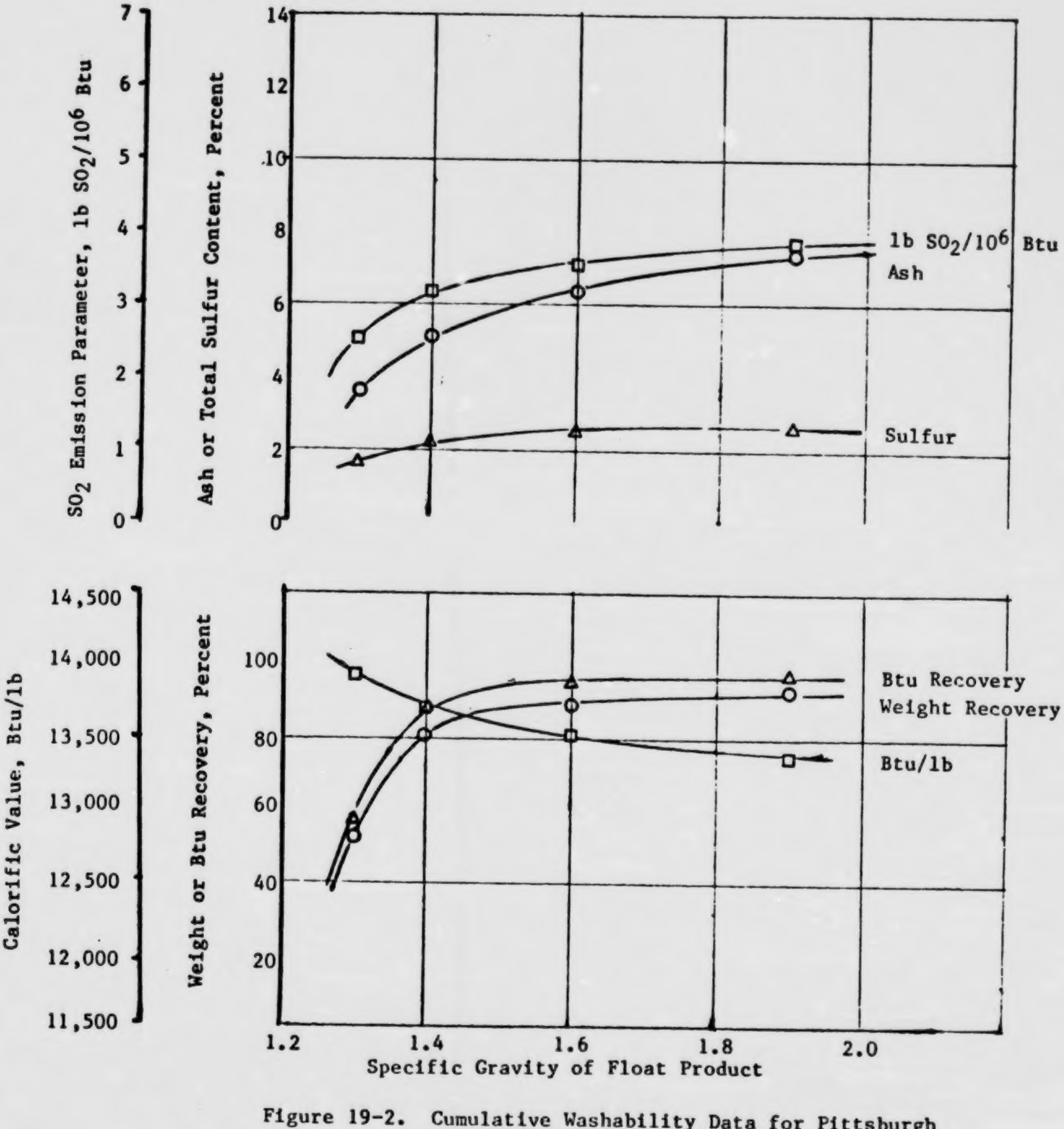
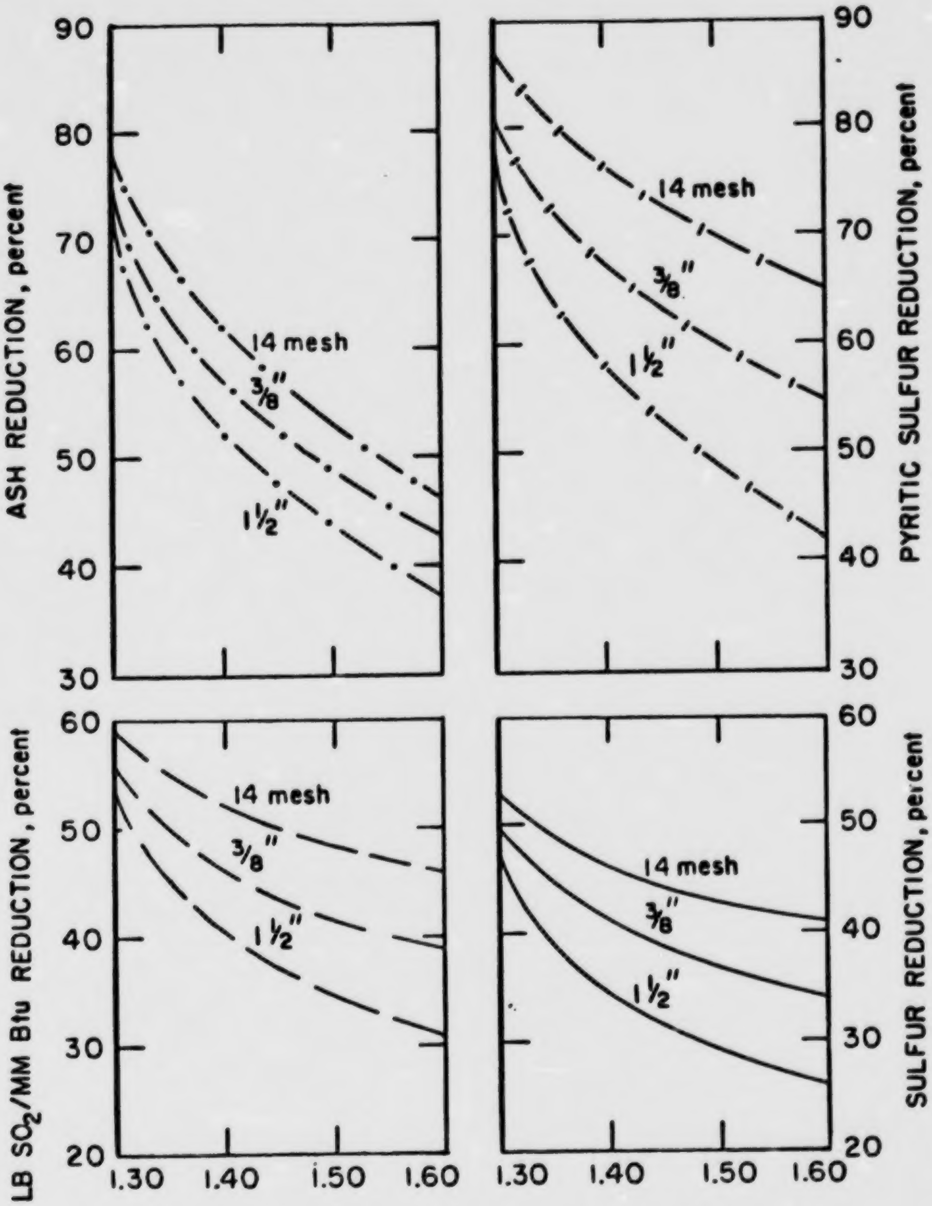


Figure 19-2. Cumulative Washability Data for Pittsburgh Coal Bed, Harrison County, Ohio (Sample Crushed to Pass 3/8-inch)(8)

The effects of size reduction and specific gravity of separation on ash, pyritic sulfur, total sulfur, and lb $SO_2/10^6$ Btu reduction are shown in Figure 19-3. These data are for the average reduction in these properties as determined by washability analysis of 227 coal samples from the Northern Appalachian coal region. The Northern Appalachian region includes the states of Maryland, western Pennsylvania, Ohio, and northern West Virginia. Although the reductions that can be obtained at low specific gravities and small particle sizes are desirable from the viewpoint of coal quality, separations at these conditions are not presently considered economically viable. At low specific gravities the coal energy losses are excessive. For example, the average Btu recovery for the 227 Northern Appalachian samples corresponding to 1.3 s.g. float product at 1-1/2 inch (37.5 mm) top size is only 37.5 percent. Alternatively, crushing all the coal to fine sizes and separating at specific gravities of 1.6 or higher would result in excessive coal preparation costs. The costs of cleaning fine coal are substantially higher than the costs of cleaning coarse coal.

Crushing coal to a top-size of 1-1/2 inches (37.5 mm) and separating the particles at a specific gravity of 1.6 provide a float sample which is representative of the product which can be obtained by many commercial coal cleaning plants. Crushing coal to a top size of 3/8-inch (9.5 mm) and separating the particles at a specific gravity of 1.3 provide a float product which can be used to represent the coal quality limit which can be achieved with advanced technologies for physically cleaning fine coal.



Northern Appalachian region (227 samples)

Figure 19-3. The Effect of Crushing Top Size and Specific Gravity of Separation on the Reduction of Ash, Pyritic Sulfur, Total Sulfur, and lb SO_2/106 Btu (8)

In a manner similar to raw coal properties, the properties of cleaned coal vary from coal bed to coal bed and coal region to coal region. Table 19-3 presents a summary of the average physical desulfurization results obtained from laboratory washability analyses for six different U.S. Bureau of Mines coal regions. The average potential raw coal SO_2 emissions for the Northern Appalachian, Eastern Midwestern, and Western Midwestern regions range from 4.8 to 9.0 lb $SO_2/10^6$ Btu (2064 to 3869 ng SO_2/J). After cleaning by crushing to 1-1/2 inch (37.5 mm) top size and taking a 1.6 s.g. float product, the average potential raw coal SO_2 emissions for these three regions range from 3.2 to 6.1 lb $SO_2/10^6$ Btu (1376 to 2622 ng SO_2/J). Although the average reduction in SO_2 emissions is about 30 percent for these high sulfur coal regions, SO_2 emission reductions for individual coals may range from less than 20 to greater than 50 percent.

The Southern Appalachian, Alabama, and Western regions contain mostly low sulfur coals. The potential raw and cleaned coal sulfur emissions from these coals generally fall in the range of 1.0 to 2.0 lb $SO_2/10^6$ Btu (430 to 860 ng SO_2/J). Some individual low sulfur coals show little or no reduction in potential SO_2 emissions when washed. Others show reductions of 25 percent and higher. The average potential SO_2 emissions reduction for cleaning low sulfur coals falls in the range of 11 to 12 percent.

Table 19-3. Summary of Average Physical Desulfurization Potential of Coals by Region(8)

(Cumulative analysis of float 1.6 product for 1-1/2 inch top size)

Coal Region	No. Samples	Face Sample Mean (lb $SO_2/10^6$ Btu)	Face Sample Std. Dev. (lb $SO_2/10^6$ Btu)	Laboratory Float-Sink Product Mean (lb $SO_2/10^6$ Btu)	Laboratory Float-Sink Product Std. Dev. (lb $SO_2/10^6$ Btu)	Percent Reduction of lb $SO_2/10^6$ Btu[a] Mean	Percent Reduction of lb $SO_2/10^6$ Btu[a] Std. Dev.
Northern Appalachian	227	4.8	2.8	3.2	1.8	31	17
Southern Appalachian	35	1.6	1.0	1.3	0.7	12	10
Alabama	10	2.0	1.5	1.7	1.3	11	8
Eastern Midwest	95	6.5	2.1	4.4	1.3	30	13
Western Midwest	44	9.0	4.5	6.1	2.5	29	13
Western	44	1.1	0.6	0.9	0.3	12	18

(a) Note that the average percent reduction in the emission parameter is not the same as the percent reduction between the mean raw and the mean product values.

COAL PREPARATION TECHNOLOGY

Coal preparation or beneficiation is used to remove mineral matter from coal. Historically, the major motivation for these activities has been to reduce the ash level in steam coals and the ash and sulfur levels in metallurgical coals. Since the advent of sulfur emission regulations, many development activities have focused on coal desulfurization.

A number of different unit operations are employed in coal preparation. They include size reduction, size classification, coal cleaning, dewatering and drying, and pollution control/waste disposal (1, 9, 10, 11, 12). Modern commercial coal preparation plants crush coal and separate the particles into a number of size ranges: coarse, medium, and fine. Each size fraction is processed in common or separate circuits using equipment suitable to the size range and cleaning objectives. Following cleaning, the coal is dewatered and sometimes thermally dried. Pollution control/waste disposal techniques are employed as needed to meet environmental regulations.

Size Reduction

Size reduction liberates mineral impurities and produces the range of sizes needed in subsequent cleaning activities. Size reduction is generally accomplished by mechanical equipment which breaks the coal by impaction, compression, splitting, shearing, or attrition. Energy usage is minimized by staged crushing and bypassing fines.

Equipment used for size reduction may include single or double roll crushers, rotary breakers, and ring-roller mills. Primary size reduction is generally accomplished by rotary breakers or crushers. The second and third stages generally use crushers or mills.

Size Classification

Size classification is generally used for: removal of fines prior to size reduction; separation of size ranges prior to further processing or sale; dewatering, separation of fines, and rinsing; and removing rock and trash. The major size classification technique used is screening. It may be performed in either a wet or dry state. Screens may be stationary or moving. The screening surface may be a perforated plate, a woven cloth, formed bars, or non-stationary parallel bars. The most common screens used in coal preparation are perforated plate and square opening wire screens that shake or vibrate. These dynamic screens are used to stratify the coal bed and separate the smaller particles which are presented to the screen apertures. Curved stationary screens called sieve bends are used to separate fine and intermediate size particles in water slurries. Classifying cyclones are also commonly used to classify fine coal particles.

State-of-the-Art Cleaning Methods

Undesirable coal constituents can be removed by either physical or chemical techniques. In physical cleaning, the organic and mineral particles are separated by techniques which rely upon differences in their size, shape, specific gravity, surface properties, electrical properties, or magnetic properties. Chemical cleaning employs chemical reactions which selectively remove mineral or organically associated constitutents. State-of-the-art cleaning methods employed in the U.S. are limited to physical techniques which rely upon specific gravity or surface property separation.

Specific Gravity Separation. The equipment most commonly used for physical cleaning relies on differences in the size, shape, and specific gravity of particles. Hydraulic washers, dense medium separators, and air concentrators are classes of equipment used in the specific gravity separation of coal. While, for the purpose of simplicity, this equipment is classified as specific gravity separation equipment, the phenomena describing separation are often complex. Separation of particles in this equipment has been described by a number of terms: stratification, hindered settling, differential acceleration, consolidation trickling, centrifugal separation, etc. A detailed description of this equipment and its operating principles is well documented (1, 10, 11).

The most popularly used hydraulic washers are jigs, hydrocyclones, and concentrating tables. The hydraulic jig is the most commonly used coal cleaning equipment (see Figure 19-4). Jigs are used to remove mineral matter and mining refuse from coarse and intermediate-size coal. The jig is operated by applying periodic hydraulic pulsations to stratify a bed of coal and gangue materials. The heavy refuse materials are removed from the bottom of the bed and clean coal particles are removed from the top.

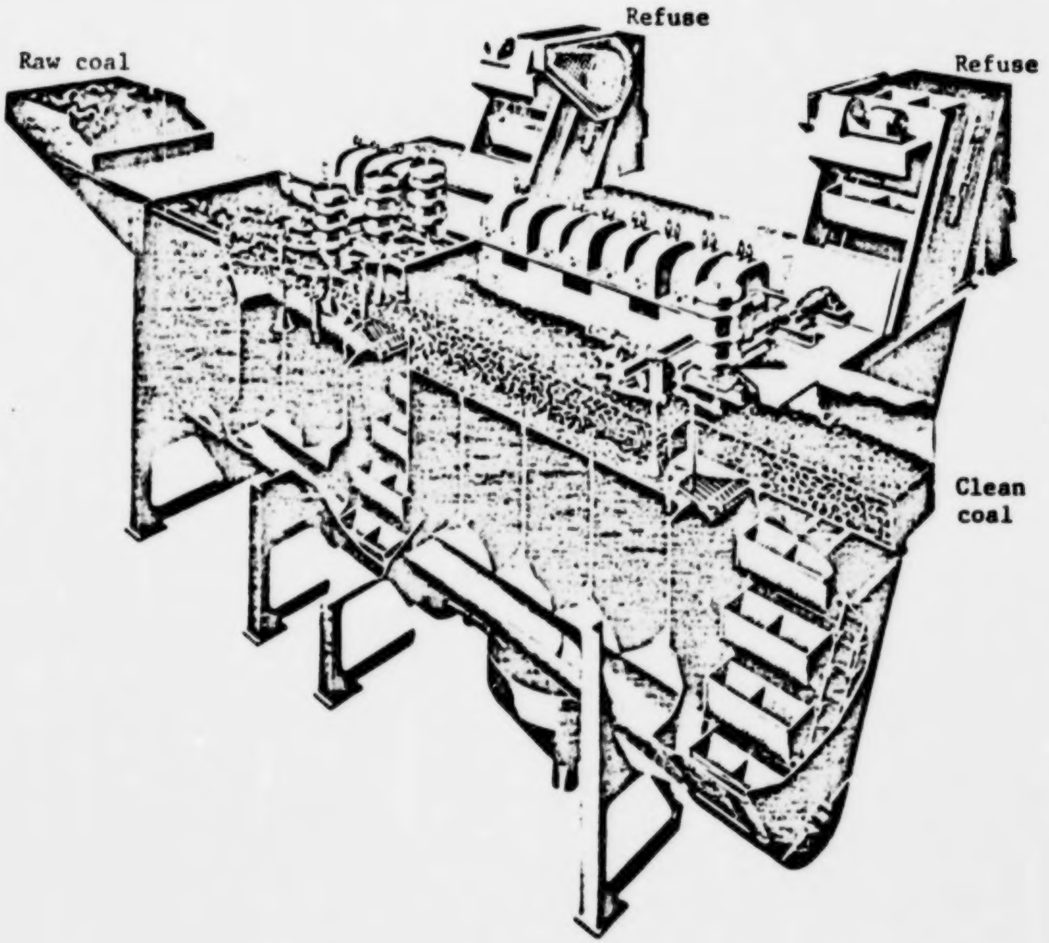

Raw coal
Refuse
Refuse
Clean coal

Figure 19-4. McNally Mogul Washer.
Source, McNally Pitsburgh, Inc.

Jigs can process large quantities of coal at low cost, but they do not efficiently separate coal and mineral particles whose specific gravity is nearly the same (near-gravity material). If a large portion of the coal pyrite is contained in the near-gravity material, sulfur removal efficiencies may suffer.

Wet concentrating tables (Deister tables) are vibrating ribbed surfaces onto which a slurry of raw coal is fed. Segregation takes place along the surface so that various regions of the table contain relatively different amounts of coal and mineral particles of different sizes and specific gravities (see Figure 19-5). Concentrating tables are generally used to wash intermediate- to fine-size coal ranging from 3/8-inch to 200 mesh (9.5 to 0.075 mm). Tables can be used effectively for separating coal and pyrite particles. While the separating efficiencies of tables are good, they require more floor space than hydrocyclones of equivalent capacity.

Hydrocyclones are also used to process medium- to fine-size coal. However, the underflow (refuse) normally contains high amounts of misplaced coal, which must be recovered by further processing. Another drawback is the large amounts of water required for proper operation. Despite these drawbacks, hydrocyclones have gained wide acceptance, as they can process large tonnages for relatively low capital investments.

Dense media separators include dense media vessels and dense media cyclones. The bulk of coal cleaned by dense media processes is cleaned in a suspension of magnetite, although organic liquids, dissolved salts in water, aerated solids, and sand/water suspension have been used

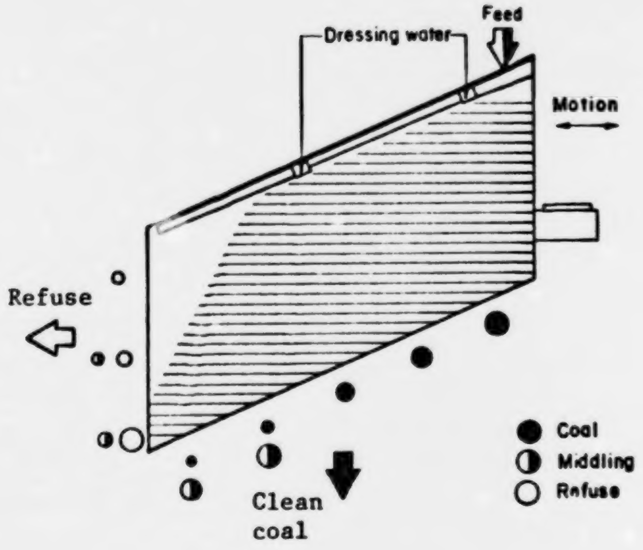

Feed
Dressing water
Motion
Refuse
Clean coal
● Coal
◑ Middling
○ Refuse

Figure 19-5. Concentrating Table - Top View

on an experimental or commercial basis. Dense media vessels are static (laminar-flowing) baths in which particles are separated by virtue of differences in their specific gravity (see Figure 19-6). The use of magnetite (5.0 specific gravity) permits practical suspension densities ranging from 81.2 to 124.9 lb/ft^3 (1.3 to 2.0 g/cm^3). For coal coarser than 1/4-inch (6.3 mm) the separation efficiency and energy recovery are between 95 and 99 percent of the values expected from laboratory float-sink tests. Dense media cyclones are used to wash intermediate- and fine-size coal. A sharp separation of coal and minerals is achieved for all particle sizes above 28 mesh (0.60 mm). Below 48 mesh (0.30 mm), the efficiency of particle separation deteriorates rapidly with decreasing particle size (13).

The increased costs of constructing and operating dense media circuits are generally offset by improvements in the product coal quality and coal recovery efficiency.

Equipment using air as a separating medium has been used for cleaning coal with sizes ranging from 3/8-inch to 48 mesh (9.5 to 0.30 mm). However, the use of this equipment has declined because of problems with separating wet coal and the costs of controlling dust emissions from the process.

Separation by Surface Properties. Cleaning processes which depend upon the differences in the surface properties of particles include froth flotation and oil agglomeration.

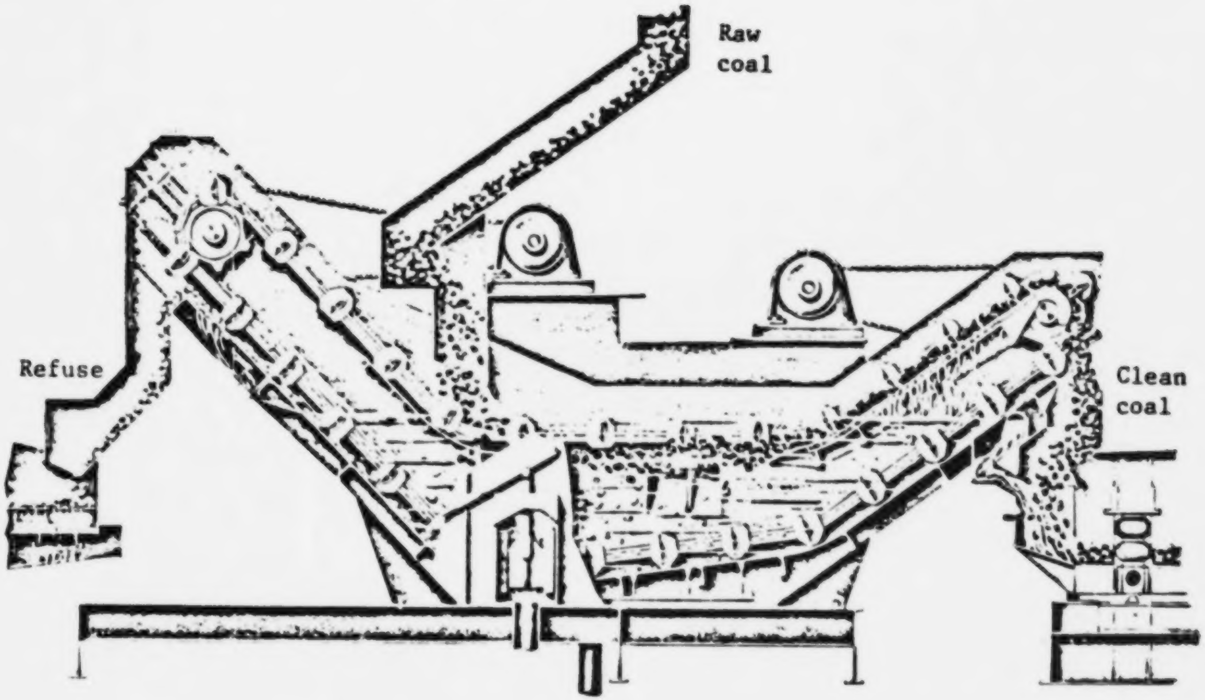

Raw
coal
Refuse
Clean
coal

Figure 19-6. McNally Lo-Flo Dense Media Vessel.
Source, McNally Pittsburgh, Inc.

Froth flotation is used to clean fine coals of particle size in the range of 28 mesh x 0 (0.60 x 0 mm). Suspensions of the finely divided coal and mineral matter are agitated in a cell with small amounts of reagents in the presence of water and air. The reagents help to form small air bubbles which collect the hydrophobic coal particles and carry them to the surface. The clean coal froth is drawn off at the top of the cell and the hydrophilic mineral matter is wetted by water and drawn off as tailings (see Figure 19-7).

The effectiveness of froth flotation varies widely with different coals depending upon the content of fixed carbon, volatile matter, and inherent moisture. In general, low-volatile bituminous coal is easier to float than high-volatile bituminous coal. Anthracite is more difficult to float, followed by subbituminous, with lignite the least floatable (14). Also, the floatability of the same rank coal depends on whether it is freshly mined or weathered (14). In addition to coal characteristics, there are many factors controlling froth flotation. The major factors affecting coal flotation are particle size, solids concentration, pH value, and the flotation reagents (1, 14, 15).

Flotation has been used primarily to remove ash from fine coal. It has not been used extensively for the removal of pyritic sulfur from coal. Because the surface properties of coal and pyrite do not differ greatly, special depressants or other coal pretreatment may be required to improve separation (15). A special two-stage froth flotation

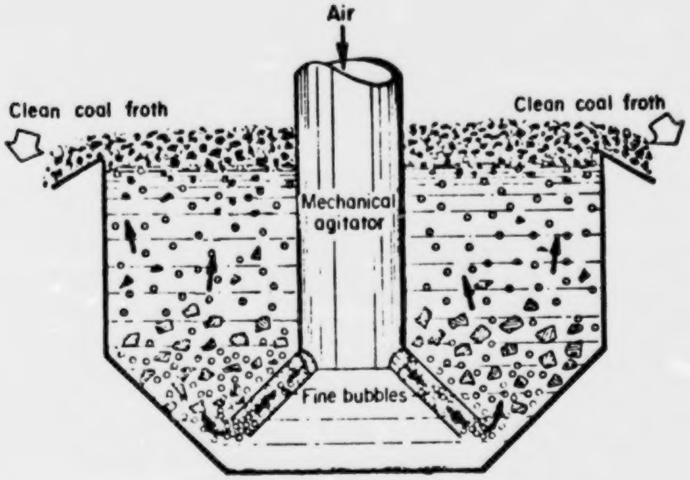

Air
Clean coal froth
Clean coal froth
Mechanical agitator
Fine bubbles

Figure 19-7. Froth Flotation Cell

method developed by the Bureau of Mines has been shown to be effective on many coals (16). In some instances, conventional flotation processes can be successful in removing pyrite. Tests at four preparation plants with conventional froth flotation circuits indicated mean ash reduction across the flotation cells ranging from 65 to 81 percent. Pyrite reductions for the same flotation circuits ranged from 48 to 65 percent (17).

While it is apparent that froth floation can be used for desulfurization of fine coal, the effectiveness of the process may vary widely depending on the coal and the design and operating conditions of the flotation circuit. It is, therefore, difficult to make generalizations concerning the potential of this technique for fine coal desulfurization.

Advanced Cleaning Techniques

A number of advanced techniques are under development for the cleaning of fine coals. The objectives of these techniques are to increase separation efficiencies of fine coal and mineral particles or to increase the amounts of sulfur which can be removed.

Oil Agglomeration. Oil agglomeration methods use a water-immiscible liquid, usually hydrocarbons, to preferentially wet and agglomerate coal particles. The small hydrophilic mineral particles remain in suspension and larger oil-coal agglomerates are separated. While oil agglomeration methods are reported to show promise in recovering very fine coal and for the selective separation of pyrite, they are not used in the U.S. on a commercial basis (15).

Electrostatic and Magnetic Cleaning. These cleaning techniques are considered important because of their potential for cleaning very fine coal. Crushing of the coal to particle sizes less than 200 mesh (0.075 mm) will liberate many of the impurities from coal; however, specific gravity and flotation separation techniques are not effective at these size ranges. While neither technique is used for commercially clean coal, substantial research has been done to evaluate these processes. Electrostatic separation is conducted on dry coal while magnetic separation may be conducted with dry coal or coal in a liquid suspension.

Early research on the electrostatic cleaning of coal indicated that cleaning is strongly and often unfavorably influenced by many variables such as the electrophysical properties of the particles, the particle size, the separator design, particle surface moisture, particle shape, and coal rank (18). However, recent developments have been made to improve the process. Laboratory tests on four Eastern and Midwestern high sulfur coals indicated sulfur reductions per million Btu ranging from 37 to 68 percent (19). The heat specific ash reductions on the same coals ranged from 25 to 59 percent. Further evaluations are now underway to evaluate the performance and economics of the process.

Recent research on magnetic separation has used high gradient magnetic separators (HGMS) or pretreated coal for use with conventional magnetic separators (20, 21). The results of a number of research projects indicate that in general, while a large fraction of the pyrite can be removed, too much coal is lost. Economic studies show that the costs for preparing the coal for the magnetic separator, and subsequent handling of the product, are much higher than the magnetic separation step itself (22). Further research is now in progress to evaluate the success of magnetic separation with a variety of process conditions.

Chemical Cleaning. Chemical cleaning processes entail grinding the coal to small particles and reacting these particles with or without chemical agents at specified temperatures and pressures. The coal's sulfur is converted to elemental sulfur or sulfur compounds which can be removed from the coal structure. Successful processes:

(1) Attack large fractions of the mineral and organic sulfur.

(2) Convert the sulfur to forms which can be readily removed from the coal structure.

(3) Minimize coal energy losses and processing costs.

While more than 30 chemical coal cleaning processes have been evaluated, the most successful in terms of total sulfur reduction involve oxidative and caustic treatments (15). Thermal decomposition mechanisms may also play an important complementary role at the elevated temperatures employed in the most successful processes.

The oxidative treatments have used air, oxygen, chlorine, nitrogen, or ferric sulfate for oxidation. The most prominent caustic treatment processes have used aqueous solutions or melts of sodium hydroxide, calcium hydroxide, or potassium hydroxide (15, 23). The most successful processes are reported to be capable of converting more than 95 percent of the pyritic sulfur and up to 50 percent of the organic sulfur to extractable forms. Reaction of more than 50 percent of the organic sulfur is difficult to achieve without substantial coal energy losses (15, 23). Organic sulfur exists in a number of functional forms, and the heterocyclic groups which appear to compose a large fraction of the total organic sulfur are resistive to chemical attack unless the carbon structure is decomposed resulting in a loss of chemical energy.

One of the least studied aspects of chemical coal cleaning is the removal or washing of reacted sulfur, ash, and reagents from the reacted coal structure. The removal of these constituents from the coal structure and the subsequent dewatering and drying operations may well be some of the most costly unit operations in chemical coal desulfurization (24).

The prospects for commercial applications of most of the processes which have been evaluated to date are questionable. The revised 1978 federal regulations for new utility boilers require reductions in the potential SO_2 emission of 70 to 90 percent before a cleaned coal can qualify as a compliance fuel. Few, if any, chemical coal cleaning processes can meet this performance requirement and compete on a cost basis with utility size FGD units (25, 26).

If chemical coal cleaning is used commercially for sulfur emission control the most likely application is the production of compliance coals for industrial boilers or the production of low sulfur and low ash fuel for use in coal-water or coal-oil mixtures.

Dewatering and Drying

Following wet cleaning methods, the coal must be dewatered by the use of vibrating screens, centrifuges, vacuum filters, or pressure filters. Thermal dryers are sometimes used to reduce the shipping weight of coal and to increase the heat content (and to prevent freezing); however, due to the cost of drying and complying with air pollution emission regulations, thermal drying is being displaced by physical drying equipment such as vacuum filters, centrifuges, or filter presses.

Pollution Control/Waste Disposal

The most concentrated source of air pollution at a coal cleaning plant is the thermal dryer. Particulate emission from the furnace may be as high as 0.0062 to 0.025 lb/ft^3 (100 to 400 g/m^3) at standard temperature and pressure (27). Stack gases from thermal dryers are usually cleaned by a combination of centrifugal collectors and high-efficiency venturi wet scrubbers (27).

Centrifugal collectors can accommodate high particle loadings and high temperatures while collecting 95 percent of the particulates from the gas stream. These collectors, however, are not effective for particles smaller than 10 μm (27). High efficiency venturi scrubbers are 95 percent efficient in collecting smaller particles, and may collect some gaseous contaminants as well.

Air pollution from transport and loading operations is difficult to control. Prevention rather than cleanup is the rule. Methods include the use of closed conveyors, spraying of water or chemicals on haul roads and storage piles, and reduction of vehicle speed on unpaved areas.

Waste materials in process waters are fine coal particles and inorganic elements and compounds dissolved from the ash in the coal. The large volumes of water used in the cleaning process and the large amount of suspended solids generated dictate that process waters be clarified and recycled. The usual means of clarification is retention in large sedimentation ponds (10).

If colloidal material from mine overburden is present, flocculants may be added to the ponds to aggregate the fine solids and facilitate clarification. Mechanical thickeners may also be used, sometimes in conjunction with flocculants. Thickeners can concentrate solids from a feed of 20 percent to an underflow of 60 percent solids, with the resultant decant suitable for recycling.

Federal standards regulate the total suspended solids, iron, pH, and (if a discharge is acidic prior to treatment) manganese of effluent discharges from coal preparation plants (28). Toxic constituents must also be reported and controlled if above certain levels, but studies have not indicated this to be a problem at operating facilities (29).

Contamination of surface or groundwater can occur from coal waste piles or storage piles, if water is allowed to infiltrate them (30). Contaminants such as iron and manganese and heavy metals such as cadmium and silver may leach from the wastes (31, 32). Because processing wastes are higher in ash (mineral) content than the cleaned coal, leachate from wastes poses the greater threat. Coal handling operations can also pollute waters if dust is allowed to settle in streams or be washed into them by precipitation and runoff.

Solid wastes from coal cleaning can be coarse or fine and consist of waste coal, slate, carbonaceous and pyritic shale, and clay. The recommended disposal method for coarse coal processing waste is deposition in layers on a cleared area, compaction, covering with earth, and ultimately revegetation (10). These procedures are designed to prevent subsidence, spontaneous combustion, and infiltration of water into the waste material. Subsurface systems are also used under waste banks to prevent water buildup that could cause structural deterioration or leachate generation. Fine refuse is discharged to settling ponds as a slurry, or dewatered and added to coarse refuse piles.

Another option for disposal of coal processing wastes is returning them to spent underground mine workings. This method is not acceptable if the mine location or the character of the waste poses a threat of contamination to an underground source of drinking water (33). These environmental considerations and the high costs of disposal have generally prohibited use of this disposal technique in the U.S.

STATUS AND DESIGN OF COMMERCIAL PLANTS

Physical coal cleaning is a mature technology. There were more than 460 operating coal cleaning plants in the U.S. in 1979 which employed wet cleaning processes. About one-third of utility coals are cleaned prior to combustion.

Level of Cleaning

Many different plant configurations employing many different types of equipment are used to clean coal in the U.S. In describing a cleaning process it is desirable to classify the preparation plant according to the complexity of the plant employed. One such approach has been to designate "levels of cleaning." Although there are many definitions of cleaning levels in the literature, it is convenient to use a system based upon the number of different coal size ranges cleaned in separate circuits and the number of product streams:

- Level 1: Mine debris and non-combustible impurities are removed. Unit operations include crushing and particle sizing.
- Level 2: Coal is crushed and classified. Coarse and medium-size coal is cleaned in a single circuit. The top size of the coarse coal may range from 4 inches (100 mm) to approximately 1/4-inch (6.3 mm). The fine 28 mesh x 0 (0.60 x 10 mm) raw coal is dewatered and shipped with the coarse coal. In some cases the fine coal is not sold but is discarded in slurry ponds.

- Level 3: Coal is crushed and classified. Coarse and medium 1/4-inch x 28 mesh (6.3 x 0.60 mm) size fractions are cleaned in separate circuits. Fine coal is treated in the same manner as for Level 2.

- Level 4: Coal is crushed and classified. Coarse, medium, and fine coal are cleaned in separate circuits. The coal from these circuits is combined to form a single product. Figure 19-8 is a schematic of a typical Level 4 plant.

- Level 5: Coal is crushed. Coarse, medium, and fine coal are cleaned in a number of different circuits. The cleaned coal from these circuits is combined to form two products: a deep cleaned coal and a middling coal. The deep cleaned coal is a metallurgical grade coal or compliance grade coal which is low in ash and sulfur. The middling coal has an ash and sulfur content which is higher than for the deep cleaned coal.

For a given coal the amount of mineral matter and sulfur which can be removed improves with the level of cleaning. So also does the capital and some operating costs (9, 34, 35). Other operating costs, such as the amount of coal lost to refuse, may be reduced as the cleaning level increases.

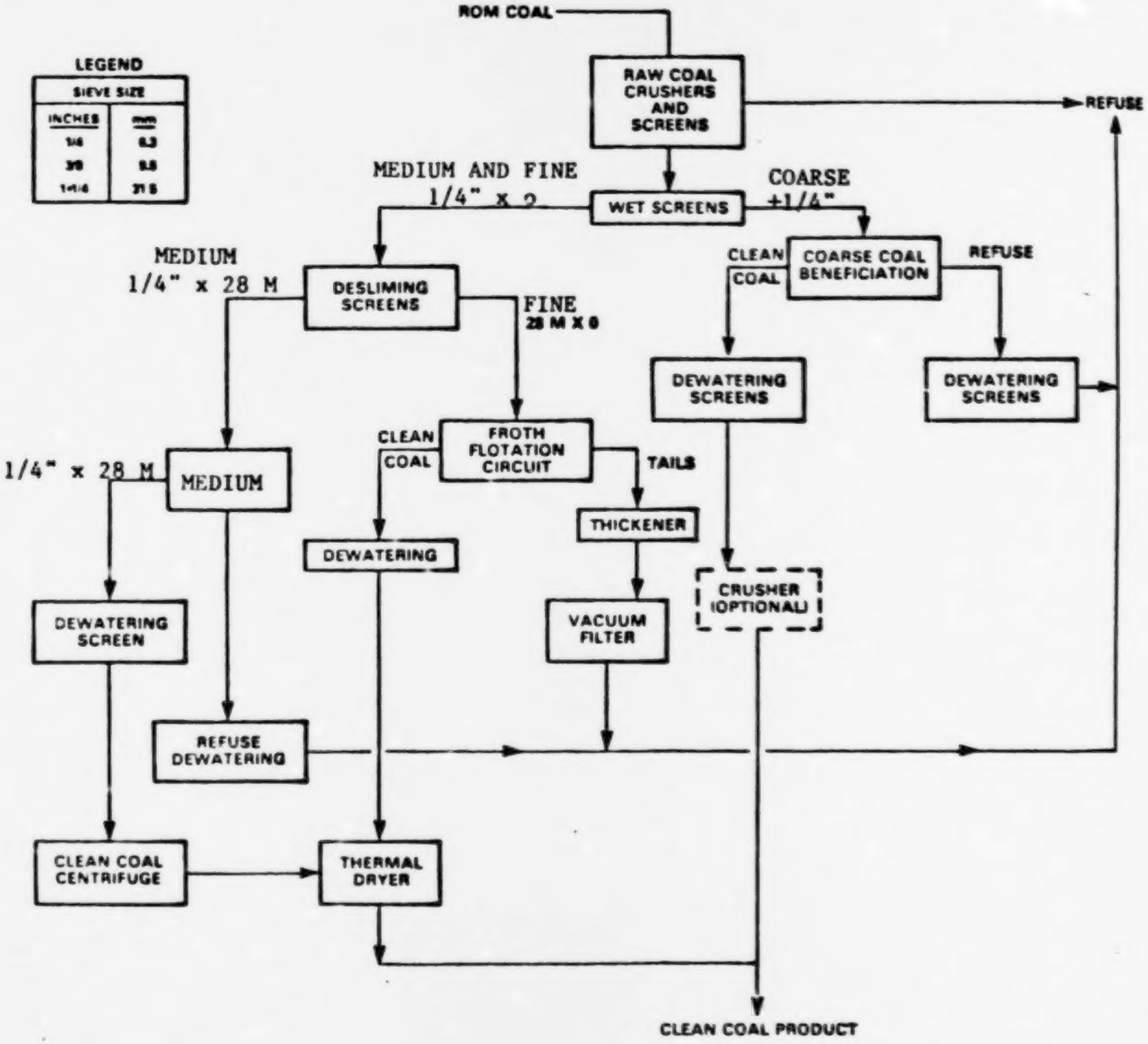

LEGEND
SIEVE SIZE
INCHES
mm
1/4
6.3
3/8
9.5
1-1/4
31.5
ROM COAL
RAW COAL CRUSHERS AND SCREENS
REFUSE
MEDIUM AND FINE
1/4" x 0
WET SCREENS
COARSE
+1/4"
CLEAN COAL
COARSE COAL BENEFICIATION
REFUSE
MEDIUM
1/4" x 28 M
DESLIMING SCREENS
FINE
28 M X 0
DEWATERING SCREENS
DEWATERING SCREENS
CLEAN COAL
FROTH FLOTATION CIRCUIT
TAILS
1/4" x 28 M
MEDIUM
THICKENER
DEWATERING
CRUSHER (OPTIONAL)
DEWATERING SCREEN
VACUUM FILTER
REFUSE DEWATERING
CLEAN COAL CENTRIFUGE
THERMAL DRYER
CLEAN COAL PRODUCT

Figure 19-8. Level 4 Coal Preparation Plant Flow Diagram

In selecting the optimum plant design for any given application, performance and cost trade-offs must be made. A balance must be made between the costs of preparation and the increased value of the product coal(s).

Plant Design Trade-Offs

Plant design and choice of cleaning equipment depend on the washability of the feed coal, the specifications of the desired product, and acceptable costs of cleaning. The major variables which can be considered when selecting a plant design include size reduction, specific gravity of separation, sharpness of separation, and number of cleaning circuits.

Size Reduction. Crushing the coal to finer sizes liberates more of the mineral particles. However, fine coal is more costly and difficult to clean than coarse coal. The increase in coal quality may not be worth the added cost.

Commercial coal preparation plants process coals with top sizes which range from approximately 4 inches to 3/8-inch (100 to 6.3 mm). No commercial plant crushes all of its coal to fine sizes before cleaning.

Specific Gravity of Separation. Reductions in the specific gravity of separation result in increased coal quality. This increased quality must be balanced against a reduction of yield and Btu recovery. Separation at low specific gravities is also more difficult. At low specific gravities a large weight fraction of the coal may lie in the specific gravity range near the separating point. The difficulty of separation increases as the amount of near-gravity material increases (material within ±0.10 of the specific gravity of separation). The result is increased amounts of misplaced material--refuse in the clean coal and clean coal in the refuse.

Sharpness of Separation. The efficiency of coal cleaning equipment in separating particles of different specific gravities is defined by a probability or distribution curve which characterizes the sharpness of separation (1). The amount of misplaced material decreases as the sharpness of separation increases. Thus, for a given yield the ash content and sulfur content of the product will decrease with increasing sharpness of separation. The calorific value and Btu recovery increase.

The sharpness of separation is a critical consideration for separations at low specific gravities. There is more near-gravity material and the amount of misplaced material will increase with decreasing sharpness of separation.

Float-sink tests give a perfectly sharp separation. The coal float-sink density distribution is the criterion against which equipment performance is measured. Dense media separators and concentrating tables produce sharper separations than jigs and hydrocyclones. A plant with dense media vessels and concentrating tables can produce a better quality coal than a plant with jigs and hydrocyclones. The marginal costs of installing and operating dense media vessels and concentrating tables must be offset by increases in the cleaned coal value.

Number of Cleaning Circuits. The sharpness of separation which can be achieved by a given type of equipment is dependent on the coal particle size. The best plant performance for a given coal top size is achieved by separating the coal with equipment which gives the sharpest separation. However, capital and operating costs increase as the number of circuits increases. A very complex plant may give a better quality product, but it may be subject to more unscheduled stoppages. Alternatively it may require a significantly higher amount of operating and maintenance labor to match the availability of a less complex plant. In many cases simplicity, reliability, and ease of operation are the main criteria on which plant design is based.

Plant Performance

The sulfur reductions and Btu enhancements (resulting from ash reductions) which are achieved at commercial coal preparation plants can result in potential reductions of SO_2 emission which range from less than 10 percent to more than 50 percent (9). Table 19-4 presents a summary of data on the performance of coal preparation plants in seven Eastern and Midwestern coal producing states. An analysis of this larger collection led to the conclusions that (9):

Table 19-4. Coal Preparation Plant Feed and Product Data[a]

Coal Region[b]	State, County, Coal Seam	Plant No., Cleaning Level[c]	Plant Feed			Plant Product			Ave. Emission Parameter Reduction, percent
			Calorific Value, Btu/lb	Sulfur Content, percent	Emission Parameter lb $SO_2/10^6$ Btu	Calorific Value, Btu/lb	Sulfur Content, percent	Emission Parameter lb $SO_2/10^6$ Btu	
NA	WVA, Harrison, Lower Freeport (6A)	52, 3	10,466	2.74	5.36	13,900	2.64	3.80	28.0
NA	OH, Perry, Ohio No. 6	20, 2	11,059	3.94	7.14	12,459	3.01	4.79	31.8
NA	Unknown, Lower KiHanning	53, 3	12,950	1.94	3.00	14,368	1.07	1.49	48.3
SA	WVA, Wise, SWVA	21, 3	9,983	0.93	1.84	14,470	1.17	1.61	10.6
SA	WVA, Wyoming	54, 3	8,167	0.70	1.70	13,242	0.91	1.38	17.0
AL	AL, Jefferson, Blue Creek	42, 4	12,150	0.77	1.27	14,258	0.60	0.84	33.9
EMW	KY, Ohio, KY No. 9 & KY No. 14	16, 2	11,325	4.15	7.36	13,164	3.19	4.84	33.9
EMW	KY, Ohio, KY No. 9 & KY No. 17	17, 2	12,234	4.30	7.03	12,974	3.38	5.21	25.3
EMW	KY, Muhlenbury KY No. 11 & KY No. 12	19, 2	10,429	4.00	7.67	12,560	3.33	5.30	30.9
EMW	IL, Randolph, IL No. 6	18, 3	10,866	4.41	8.12	12,048	3.84	6.37	21.6

(a)Data are for weighted plant averages calculated from data in Ref. 9, Appendix C.

(b)NA - Northern Appalachian, SA - Southern Appalachian, AL - Alabama, EMW - Eastern Midwest.

(c)Plant No. corresponds to plant No. given in Ref. 9.

(1) Physical coal cleaning is an effective technology for reducing SO_2 emissions from coal combustion. The sulfur emission parameter (lb $SO_2/10^6$ Btu) of the coal is significantly reduced by coal cleaning. The average reductions achieved for different coal regions using data provided by coal companies were 33 percent for Northern Appalachian coals, 23 percent for Southern Appalachian coals, and 30 percent for Eastern Midwestern coals.

(2) In terms of the sulfur emission parameter, the preparation plants reduced the mean, standard deviation, and relative standard deviation (standard deviation/mean) of the product coal in almost every case. The only exceptions were plants cleaning low sulfur Southern Appalachian coal.

(3) The difference in reductions of the sulfur emission parameter between cleaning levels 2, 3, and 4 is small, although cleaning level 4 (deep cleaning) always showed the greatest reduction on a regional basis.

Table 19-5 presents a comparison of plant performance data and washability data (9, 36). The emission and percentage reduction estimates are given as average state values. The washability data are for the 1.6 s.g. float product of coal samples which were crushed to a top size of 1-1/2 inches (37.5 mm). The emission reduction estimates for the plant data range from 22.0 to 41.2 percent. Emission reduction estimates for the washability data range from 10.1 to 32.2 percent. The comparisons

Table 19-5. Comparison of Plant and Laboratory Washability Emission Parameters (lb $SO_2/10^6$ Btu)(a)

	LABORATORY DATA(b)				PLANT DATA(c)			
Region and State	No. Samples	Raw Coal	Clean Coal	Reduction, Percent	No. Plants	ROM Coal	Product Coal	Reduction, Percent
Northern Appalachian								
Pennsylvania	170	3.9	2.4	32.2	4	3.1	1.8	35.9
Ohio	90	5.7	4.2	25.9	4	7.3	5.0	32.2
N. West Virginia	30	4.8	3.4	28.6	9	4.8	3.6	26.0
Southern Appalachian								
S. West Virginia	16	1.4	1.2	10.1	19	1.8	1.3	22.0
Alabama								
Alabama	10	1.9	1.7	10.8	4	2.2	1.2	41.2
Western and Eastern Midwest								
Indiana	21	5.9	4.3	26.4	3	8.0	5.2	35.6
W. Kentucky	37	6.7	4.5	31.5	3	7.5	5.2	29.6
Illinois	40	6.5	4.4	29.3	10	8.1	6.0	27.9

(a) State averages for the indicated number of washability samples and number of plants.

(b) Laboratory data from Ref. 36 for 1-1/2 in. (37.5 mm) top size and 1.6 s.g. separation. Percentage reduction values were given. The raw and clean coal emission parameters are estimated using the average sulfur and heating values of coal from each state.

(c) Plant data summarized from Ref. 9, Appendix C.

are judged to be quite good considering the facts that (1) data are matched only on a regional and state basis, and (2) there are not enough data to obtain accurate averages for each state.

However, while the plant and washability data appear to fall in the same range, the plant raw coal emission data and the plant percentage reduction data are at times substantially higher than the corresponding washability data. This probably results from the fact that the run-of-mine (ROM) heating value of the plant feed is low in relationship to the raw coal washability samples. Modern mining techniques (continuous and long-wall miners) often remove roof, floor, and parting materials, called dilution material, along with the coal. The washability data in Tables 19-2 and 19-3, and those most commonly given in the literature, were derived from coal mine face samples. These face samples differ from ROM samples in that they do not include major partings, roof or floor materials. The roof and floor materials, which may also contain sulfur, reduce the heating value of the ROM samples, and result in higher ROM sulfur emission parameter and a higher potential reduction of this parameter when compared with face samples.

Since there is little ROM washability data it is desirable to use the face sample washability data to estimate the performance of plants designed for controlling SO_2 emissions. Studies show that face sample washability data can be used as a surrogate for estimating the performance of coal preparation plants (9, 36). In one study, data on the feed coals from 85 coal preparation plants were used along with laboratory washability data to predict the sulfur and Btu content of the cleaned coal (36). Since the washability data were not available for the feed coal, the cleaned coal properties were predicted by multiplying the feed coal properties by the ratio of the corresponding cleaned to uncleaned coal properties for similar coals in the washability data base using a computer program called the Coal Assessment Processer (CAP)*. Two washability conditions were used. The first, designated as PCC-1, was for crushing to a 1-1/2 inch (37.5 mm) top size and taking a 1.6 s.g. float product. The second, designated as PCC-2, was for crushing to a 3/8-inch (9.5 mm) top size and taking a 1.3 s.g. float product. These predicted results were compared with the clean coal product data from the 85 coal preparation plants. Figure 19-9 shows the results of these comparisons.

It can be concluded from Figure 19-9 that laboratory washability results obtained by crushing face samples to 1-1/2 inches (37.5 mm) and taking a 1.6 s.g. float product provide a good first approximation of the likely performance of a level 3 or level 4 coal preparation plant. The exact SO_2 emission value predicted for the cleaned coal will be somewhat uncertain because of (1) differences in ROM and face samples, and (2) plant and washability performance differences which result from differences in the sharpness of separation. Laboratory washability data

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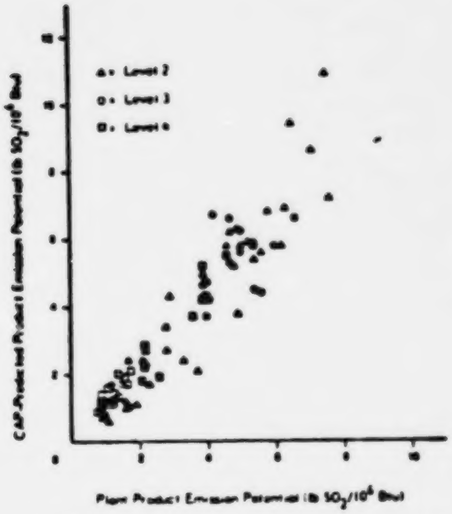
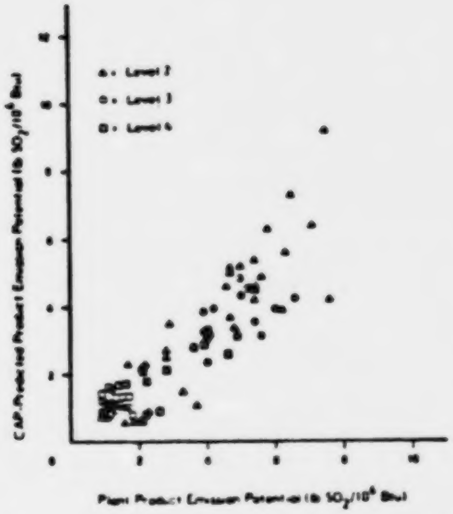
*Washability data were assigned to each coal preparation plant by matching the closest coal compositions (in a least squares sense) using washability data from the same state, county, and coal bed. If there were no washability samples in the same county, then state, region, and coal bed matches were used.



Cleaning Level	Regression Equation	Correlation Coefficient (r)
2	Y = 1.28X - 0.71	0.96
3	Y = 1.07X + 0.02	0.92
4	Y = 1.10X + 0.06	0.97
All	Y = 1.17X - 0.21	0.96

Figure 19-9.a. Comparison of PCC-1 Computer Model Results with Coal Preparation Plant Performance



Cleaning Level	Regression Equation	Correlation Coefficient (r)
2	Y = 0.96X - 0.40	0.67
3	Y = 0.72X + 0.23	0.90
4	Y = 0.63X + 0.31	0.86
All	Y = 0.85X - 0.08	0.89

Figure 19-9.b. Comparison of PCC-2 Computer Model Results with Coal Preparation Plant Performance

corresponding to separations at lower specific gravities can be used to estimate potential improvements which can be made for different design and operating conditions. However, these estimates will be more speculative because of the increased importance of sharpness of separation criteria at low specific gravities.

Costs of Cleaning

The cost of coal cleaning is a function of level of cleaning, percentage of material discarded as refuse, coal washability, and plant size. The cleaning costs are not strongly influenced by the coal sulfur content. There is potentially a wide range of costs for coal cleaning, and the costs for each plant must be considered individually with respect to location, terrain, coal properties, preparation specifications, and coal production rate. The costs of cleaning can be summarized in terms of the total capital requirements and annual costs.

Capital Requirements. The total capital requirements include direct costs, indirect costs, contingencies, land, and working capital. Direct costs include raw coal storage and handling equipment costs, preparation plant equipment cost, and facility costs. Facility costs are normally estimated to be some fixed percentage of equipment costs. Indirect costs include engineering costs, construction costs, and field expenses. Total capital requirements are generally 1.6 to 2.3 times higher than total direct costs (26, 35, 37).

Table 19-6 presents estimates of the total capital requirements for three levels of cleaning for each of five different coals. These costs were taken from a 1981 Electric Power Research Institute (EPRI) study on the impact of coal cleaning on the cost of new coal-fired power generation (35). The costs for treating two additional coals at three levels of cleaning are also contained in the 1981 EPRI study. They were not included here because of space limitations.

Each coal preparation plant in the 1981 EPRI study was designed to provide coal for a 1000 MW power plant. The capacity and annual production rate of each treatment facility, therefore, changes as the properties of raw and cleaned coal vary. In the 1981 EPRI study, each of the coals was treated at three different levels: screening and crushing (level 1), partial preparation (level 2), and intensive cleaning (level 4). All costs in the study were expressed in mid-1978 dollars. Note that these costs are outdated because of inflation and that they are used here to illustrate the relative importance of various coal preparation cost components.

Table 19-7 provides a summary of the raw and cleaned coal properties which result from preparing these five coals (A through E) to three levels each (1, 2, and 4). For each coal the ash content is decreased and the calorific value is increased as the level of cleaning increases. The sulfur contents of some coals are reduced while others remain essentially constant. However, in all cases the SO_2 emission parameter

Table 19-6. Coal Preparation Plant Costs for Five Coals When Prepared at Levels 1, 2, and 4(a)

Coal: State; Seam; County	Cleaning Level	Annual Coal Rate(b) 10^3 tpy	Total Capital(c) Requirements 10^3 \$	Unit Annual Costs, \$/ton of Prepared Coal				
				ROM(e) Coal	Preparation(e)	Waste Disposal	Total Prepared	Incremental
A: IL; No. 6; Macoupin	1	3,120	7,370	21.39	0.78	-	22.17	-
	2	2,944	17,820	23.74	1.80	0.20	25.74	3.57
	4	2,820	31,620	24.62	3.09	0.28	27.99	5.82
B: WVA; Cedar Grove; Logan	1	2,592	7,310	23.39	0.93	-	24.32	-
	2	2,296	20,550	27.67	2.89	0.35	30.91	6.59
	4	2,242	31,180	28.00	4.17	0.37	32.54	8.22
C: AL; American & Mary Lee; Walker	1	3,224	7,490	22.39	0.77	-	23.16	-
	2	2,908	17,090	25.55	1.76	0.28	27.59	4.43
	4	2,540	31,390	28.99	3.44	0.58	33.01	9.85
D: IA; Lower Ford; Panora	1	3,276	7,430	19.39	0.75	-	20.14	-
	2	3,206	15,730	20.47	1.45	0.10	22.02	1.88
	4	3,154	34,760	21.46	2.93	0.24	24.63	4.49
E: UT, Rock Canyon, Gilson, Sunny Side; Carbon	1	3,172	7,330	19.39	0.76	-	20.15	-
	2	2,662	17,220	23.97	1.93	0.46	26.36	6.21
	4	2,558	31,640	24.41	3.50	0.51	28.42	8.27

(a) Data adapted from Reference 35. A = case 1, B = case 3, C = case 4, D = case 6, and E = case 7 in the 1981 EPRI study. All capital and first year unit annual costs are presented in mid-1978 dollars.

(b) Prepared coal on an "as-received" basis. Rate required to produce a net 1000 MW electricity in a new power plant.

(c) Capital costs can be updated using an inflation factor developed from Chemical Engineering Plant Cost Index. Example: (\$31.620 million in mid-1982 \$) x 1.46 = \$46.165 million in first quarter 1982 \$.

(d) ROM coal costs = cost of as-mined coal cost in \$/ton ÷ (preparation plant yield/100) + UMW pension and trust fund of \$1.39/ton. Coal costs can be updated by assuming a 6.2 percent annual inflation rate (35). The inflation factor for first quarter 1982 dollars is 1.25. Example: (\$24.62/ton in mid-1978 \$) x 1.25 = \$30.77/ton in first quarter 1982 \$.

(e) Mean first year cost ÷ annual prepared coal rate. Capital costs can be updated using a weighted average of labor, electricity, material, and capital cost inflation factors. Example: (\$3.09/ton in mid-1982 \$) x 1.32 = \$4.08/ton in first quarter 1982 \$.

Table 19-7. Summary of Raw and Cleaned Coal Properties for Five Coals When Prepared at Levels 1, 2, and 4[(a)]

Coal: State; Seam; Mine Type	Cleaning Level	Yield, percent	Btu Recovery, percent	Ash Content,[(b)] percent	Sulfur Content, percent	Calorific Value, Btu/lb	Potential Emissions, lb SO_2/10^6 Btu	Emission Reduction,[(c)] percent
A: IL; No. 6; Deep	1	100	100	16.5	3.39	9,860	6.88	-
	2	89.5	95.1	12.0	3.26	10,480	6.22	9.6
	4	86.1	94.9	9.2	3.23	10,870	5.94	13.7
B: W VA; Cedar Grove; Deep	1	100	100	16.0	0.85	11,680	1.46	-
	2	84.6	94.1	7.5	0.83	13,130	1.26	13.7
	4	83.6	95.1	5.5	0.84	13,430	1.25	14.4
C: AL; American & Mary Lee; Deep and Surface	1	100	100	27.0	1.26	9,450	2.67	-
	2	86.9	96.3	20.7	1.28	10,470	2.45	8.2
	4	76.1	95.8	12.2	1.28	11,910	2.15	19.5
D: IA; Lower Ford; Surface	1	100	100	15.1	6.90	9,450	14.60	-
	2	94.3	96.1	13.8	5.46	9,630	11.34	22.3
	4	87.6	93.4	10.2	4.66	9,840	9.47	35.1
E: UT; Rock Canyon, Gilson, and Sunny Side; Deep	1	100	100	22.9	0.64	9,650	1.33	-
	2	79.7	94.1	11.4	0.63	11,390	1.11	16.5
	4	78.2	96.0	8.4	0.62	11,850	1.05	21.1

(a) Data adapted from Reference 35. Level 1 = screening and crushing (raw coal), Level 2 = partial preparation, and Level 4 = intensive preparation.

(b) Coal properties on an "as-received" basis.

(c) Two coals not summarized here were from the Pittsburgh Seam in WVA and the Rosebud Seam in MT. The Level 2 and Level 4 emission reductions for these coals were: WVA coal, 13.3 and 21.5 percent; MT coal, 9.3 and 27.9 percent.

decreases with increased level of cleaning. A portion of this reduction in all cases results from an increase in the coal calorific values. In other cases it also results from a reduction in coal sulfur content.

Plant yields for the five coals decrease with increasing level of cleaning. Level 2 yields range from 79.7 to 94.3 percent. Level 4 yields range from 76.1 to 87.6 percent. Although, the plant feed material was adjusted to include dilution material from mining (roof, floor, and parting material), these yields are moderately high. Based on the calorific values of the feed and product coal, the removal of ash and dilution material during cleaning may result in yields as low as 50 percent in some commercial plants (9).

The Btu recovery may decrease or increase with an increasing level of cleaning (see Table 19-7). Btu recoveries in the level 2 plants range from 94.1 to 99.1 percent. In the level 4 plants the Btu recoveries range from 93.4 to 96.0. An increase in Btu recovery when cleaning from level 2 to level 4 can result from the use of equipment in the level 4 plant which improves the sharpness-of-separation. A reduction in Btu recovery occurs in the level 4 plants when Btu losses at lower specific gravity separations are not offset by Btu recovery gains related to the sharpness-of-separation.

The total capital requirements for level 1 preparation--which includes: screening, crushing, coal sampling, crushed coal storage, and unit train loadout facilities--vary little from coal to coal (see

Table 19-6). The average for the five level 1 plants is $7,386,000. The total capital requirements for the five level 2 plants range from $15,730,000 to $20,550,000. Included in these costs are provisions for raw coal screening and crushing, a raw coal storage silo, clean coal samplers, clean coal storage silos, and unit train loadout equipment. The cleaning circuit for each of the level 2 plants is nearly identical. In all cases a baum jig is used to wash 4 inch x 0 (100 mm x 0) coal. Cost differences between level 2 plants result primarily because of differences in equipment used for dewatering the clean coal and refuse. The lower capital cost plants correspond to those plants which use only screens and centrifuges for dewatering of coal and refuse. Most of the other plants employ screens, centrifuges, thickeners, and vacuum filters for dewatering of the coal and refuse. The plant with the highest capital cost also contains a thermal dryer for drying of the intermediate and fine size coal.

Total capital requirements for the five level 4 plants in the 1981 EPRI study ranged from $31,180,000 to $34,760,000. The level 4 plants all employ dense media vessels for cleaning of the coarse 4 x 1/4-inch (100 x 6.3 mm) coal, heavy media cyclones or concentrating tables for cleaning the medium 1/4-inch x 28 mesh (6.3 x 0.60 mm) coal, and concentrating tables or froth flotation for cleaning the fine 28 x 0 mesh (0.60 x 0 mm) coal. Cost differences between the plants result primarily from differences in the intermediate and fine coal cleaning equipment and associated dewatering and drying equipment. Other cost differentials arise from the variation in plant capacity.

Economies of scale can be obtained through the use of large preparation plants. Cost economies result primarily from the fact that costs per unit of capacity decrease with increasing size of equipment and facilities. Capital costs for larger or smaller plants may be estimated by use of the 0.7 power rule which states that the ratio of capital costs is proportional to the ratio of plant capacities raised to the 0.7 power. Thus, if the 609 ton/h (544 Mg/h) clean coal capacity of the level 4 plant cleaning in case B were to be increased to 1200 ton/h (1088 Mg/h), the total capital investment may be estimated to be:

$$\$31.2 \text{ million} \times \left(\frac{1200}{609}\right)^{0.7} = \$50.2 \text{ million}$$

Economies of scale are also reflected in annual costs in the form of reduced unit costs related to operating and maintenance expenses.

The 0.7 power rule evidently does not apply to modular plants. Plant modules are available at feed size ranges of 100, 150, and 200 ton/h (91, 136, and 181 Mg/h). Different types of modules available include those for heavy media, jig, hydrocyclone, and concentrating table processes. It is sometimes possible to cut the total capital requirement of a conventional level 2 plant expressed in $ per ton-hour of feed by as much as 25 percent by using a modular plant (38). Unfortunately, modular plants cannot generally achieve the levels of performance which can be attained in a conventional level 4 plant.

Annual Costs. Annual costs include: material costs, operating and maintenance costs, overhead expenses, and capital charges (amortization, taxes, and return on investment). Annual charges are often expressed in terms of $/ton of cleaned coal. To assess the cost differences between plants and to determine the costs of various activities, it is convenient to break down the unit annual costs for coal preparation into a number of different components:

- ROM coal cost - This cost includes two terms: (1) the cost of mining a ton of coal divided by the preparation plant yield, plus (2) the contribution to the United Mine Workers of America (UMWA) pension/benefits fund per ton of coal shipped from the preparation plant. The first term accounts for the ROM material which ends up as clean coal and that fraction of coal which must be mined then discarded as refuse.

- Coal preparation cost - This cost is for size reduction, size classification, coal cleaning, dewatering and drying, and pollution control. The cost of raw coal storage, clean coal storage, clean coal loadout system, and refuse disposal can also be included in the coal preparation cost. If these and other "grass roots" plant costs are included, then the capital cost of coal preparation will be 2 to 3 times the cost of a "battery limits" plant (1). Accordingly, annual costs will also be higher. Equipment costs, facility costs, and operating expenses included in various coal preparation plant cost estimates will be dependent on whether the plant is a mine-site plant, a central cleaning plant, or a power plant site facility. It will depend upon the essential facilities and operations which are charged to the mining and power plant costs, rather than to the preparation plant account.

- Waste disposal cost - This cost is sometimes included in a separate category.

- The total cost of prepared coal or cleaned coal - This cost includes the ROM coal cost, the coal preparation cost, and the waste disposal cost.

- Cost of mined and discarded material - This cost can be defined as the sum of the ROM coal cost and the refuse disposal cost at a given level minus the level 1 ROM coal cost.

- Incremental cost of cleaning to higher level - This cost is defined as the total cost of prepared coal at a given cleaning level minus the total cost of prepared coal at some lower cleaning level.

Unit annual costs for cleaning five coals at three different levels are given in Table 19-6. The ROM coal costs and refuse disposal costs increase with the level of cleaning due to decreasing plant yield. The preparation costs also increase with level of cleaning due to increases in capital costs and operating expenses. Level 1 preparation costs range from \$0.75/ton to \$0.93/ton (\$0.83/Mg to \$1.03/Mg). The level 2 preparation costs range from \$1.45/ton to \$2.89/ton (\$1.60/Mg to \$3.19/Mg). This wide range of preparation costs is in part due to differences in capital costs and operating expenses. It is also due in part to differences in the clean coal production rate. For low production rates, unit annual costs are spread over a smaller number of units. Unit annual costs based solely upon the tonnage of material produced penalize the plants which produce a high calorific value coal. In these cases more appropriate unit measures of cost would be $/$10^6$ Btu or $/kWh. However, the $/ton costs are widely used because coal is most commonly sold on a weight basis.

Level 4 preparation costs in Table 19-6 range from $2.93/ton to $4.17/ton ($3.23/Mg to $4.60/Mg). The low costs correspond to a high production rate with a modest amount of coal dewatering operations. The high costs correspond to low production rates and extensive dewatering and drying.

The total cost of prepared coal in Table 19-6 ranges from $20.14/ton to $33.01/ton ($22.20/Mg to $36.39/Mg). In all cases the cost of prepared coal increases with level of cleaning. Increased incremental costs for cleaning from level 1 to level 2 range from $1.88/ton to $6.59/ton ($2.07/Mg to $7.27/Mg). Incremental costs for cleaning from level 1 to level 4 range from $4.49/ton to $9.85/ton ($4.95/Mg to $10.86/Mg). These incremental preparation costs are the net costs added to a ton of cleaned coal by preparation (level 1 corresponds to raw coal). The incremental costs above level 1 consist of three components: the coal preparation costs, the costs of material mined and discarded material, and the costs of waste disposal. For level 2 plants, the costs of preparation range from $1.45/ton to $2.89/ton ($1.60/Mg to $3.19/Mg), while the costs of the mined and discarded material, as calculated from Table 19-6, range from $1.18/ton to $5.04/ton ($1.3/Mg to $5.56/Mg).

For level 4 plants the costs of preparation range from $2.93/ton to $4.17/ton ($3.23/Mg to $4.60/Mg), while the calculated costs of the mined and discarded materials range from $2.31/ton to $7.18/ton ($2.55/Mg to $7.92/Mg). Waste disposal costs, which are a portion of the costs of mined and discarded material, range from $0.10/ton ($0.11/Mg) to $0.58/ton ($0.64/Mg) depending on the coal and level of cleaning.

The cost of mined and discarded material is a measure of costs related to both the coal quality and mining practice. Coal preparation removes the extraneous minerals which are intimately associated with the coal facies. It also removes dilution material which originates in the mine roof, mine floor, and coal seam partings. Modern mechanical mining methods are not selective, and they often result in ROM coal which contains large quantities of dilution materials. It is not unusual to discard more than 40 percent of the material which is removed from modern underground mines. While this adds substantially to the total costs of prepared coal, the ROM coal could not be sold unless it were cleaned. Although the costs of mining and discarding dilution materials are often attributed to the "costs of cleaning," it is more appropriate to charge them to the costs of producing a marketable coal. In this fashion the "costs of cleaning" can then be defined as the incremental costs of cleaning to higher levels; i.e., incremental levels which are above the base level needed to market the mined material. In most cases the base level would be level 2 cleaning. If increases in the incremental costs of cleaning are more than offset by increases in the value of the product coal, then higher levels of cleaning are warranted.

The benefits of cleaning must outweigh the costs, otherwise a buyer would purchase raw coal or coal cleaned to a lower level.

Cost Benefits. Cost benefits may accrue from a reduction in transportation costs, coal handling costs, ash disposal costs, boiler capital costs, boiler operating costs, and flue gas cleaning costs. Cost penalties may result from an increase in the amount of coal fines and the surface moisture content. Large amounts of fines and frozen coal (a consequence of additional moisture) increase handling costs.

Cost benefits which occur from reduced transportation and boiler ash disposal costs are well known. These costs are coal and site specific. Transportation and boiler ash disposal cost savings are increased as the amount of ash which is removed by cleaning is increased. Potential cost savings also increase as coal transportation and ash disposal distances increase.

The use of cleaned coal can result in the reduction of the capital costs of new steam-generators. These cost reductions result from cost savings in: the firing equipment (pulverizers, fuel piping, wind boxes, etc.); the boiler design (furnace volume, heat transfer surface arrangement, tube spacing, soot blowing, etc.); the coal handling and storage equipment (conveyors, bunkers, etc.); and ash handling and storage. Most of these steam-generator capital costs generally decrease with reductions in mineral (ash) content. Reductions in the sulfur content can also result in lowered problems with fireside performance and, hence, can lead to a less conservative, lower cost design. In most cases, increasing the level of cleaning to produce a better quality coal should result in lower capital costs for new boilers.

Boiler operating costs are affected by boiler efficiency, boiler availability, and boiler maintenance costs. These factors are in turn affected by coal quality. Excessive slagging or fouling of boiler heat transfer surfaces by coal minerals results in a reduction of heat transfer efficiencies. A major factor in boiler availability is boiler tube failure. Boiler tube failures can result from many causes, including fly ash and soot blower erosion, external corrosion, iron attack, slag erosion, and slag falls. A reduction in coal sulfur and ash content can reduce fuel related tube failures and result in increased boiler availability. Plant equipment with maintenance expenses related to coal quality may include: coal breakers, boilers and accessories, soot blowers, coal transport piping and valves, boiler room scale and feeders, pulverizer mills, burners and lighters, air preheaters, ash crushing equipment, and ash disposal piping systems. Reducing the ash and sulfur content of coal can reduce boiler maintenance costs.

Flue gas cleaning costs are also reduced by coal cleaning. Particulate control device capital and operating expenses are generally reduced as the amount of ash which must be collected is reduced. Flue gas desulfurization (FGD) costs are reduced with the decreasing sulfur and ash content of the coal. In many cases, major FGD cost reductions result because (1) a portion of the flue gas can be bypassed, reducing the volumetric flow through the scrubber, (2) with by-pass, flue gas reheat requirements are decreased, (3) the quantities of limestone or other chemical reagents are reduced, and (4) FGD sludge quantities which must be disposed of are reduced.

A number of studies have attempted to quantify the cost benefits of improved coal quality which can be achieved by coal cleaning (39 through 47). Others have attempted to assess the impacts of coal cleaning on the costs of SO_2 emission control or the costs of power generation (26, 35, 48, 49). They too have attempted to quantify the cost benefits of cleaning. In all of these studies the most elusive cost benefits have been those related to boiler capital costs and boiler operating expenses.

In the 1981 EPRI study on the cost of new power generation, it was estimated that the costs of new steam generators can be reduced by coal cleaning (35). In the seven cases studied it was estimated that coal cleaning could reduce the total capital requirement for new 1000 MW power plants by 0.3 to 5.0 percent. This represented capital cost savings ranging from $2.3 to $39.5 million. These savings were exclusive of savings which could be achieved by cost reductions in the FGD system or boiler/FGD waste disposal. Most of the cost savings were achieved in firing system cost reductions. The cost reductions were dependent on the coal and level of cleaning. In all cases the cost savings increased with increased level of cleaning.

Estimates of boiler operating cost benefits are based on studies which show that coal with high sulfur and ash contents generally result in decreased boiler efficiency and boiler availability, and increased boiler maintenance costs (39, 41, 42, 43, 44, 45, 46, 47). Early studies based on limited data estimated that boiler-related cost benefits may range from less than \$1/ton to more than \$7/ton (\$1.1/Mg to \$7.7/Mg) of coal burned (39, 41). Contrary to these estimates, an EPRI study on the impact of cleaned coal on power plant performance and reliability failed to find significant differences in the boiler operating costs at two plants that switched from run-of-mine to washed coal (40). However, recent studies supported by Tennessee Valley Authority (TVA) and Department of Energy (DOE) have confirmed the relationship between coal quality and boiler operating costs (43 through 47). These studies involved the evaluation of operating data collected over a period of 19 years from 58 TVA boilers. Major findings of the studies were:

- Boiler Efficiency - Major factors influencing boiler efficiency include coal ash content, coal moisture content, and boiler age. Sulfur content does not appreciably affect efficiency. A large change in coal, ash, and moisture content can have a significant impact on boiler efficiency. For example increasing coal ash from 10 to 20 percent and moisture from 6 to 10 percent can reduce boiler efficiency by approximately 0.77 percent (44).

- Boiler Availability - Forced outage hours attributed to coal related equipment are a function of coal ash content, coal sulfur content, and boiler age. Models based on TVA data predict that switching from a very good coal (1.0 percent sulfur and 12.0 percent ash) to a very poor coal (5.0 percent sulfur and 24 percent ash) would increase the forced outage rate in a "typical" TVA plant by 850 hours per year (45).

- Maintenance Costs - Of 10 plants analyzed, 7 showed correlations between coal quality and maintenance costs when cost data were evaluated according to the annual consumption of ash and sulfur. The degree of correlation varied significantly between the fuel-related cost centers at each plant as well as between various plants. Plantwide maintenance cost dependencies were non-linear. The logarithm of maintenance costs increased proportionately with the annual plant consumption of ash and sulfur. Using a plantwide maintenance cost saving model it was estimated that plants in the TVA system can save between \$0.05/ton and \$0.10/ton (\$0.06/Mg and \$0.11/Mg) of coal burned for each 1 percent reduction in ash. Similarly, for each 1 percent reduction in sulfur, between \$0.30/ton and \$0.50/ton (0.33/Mg and \$0.55/Mg) can be saved for each ton of coal burned. Substantial cost savings can be achieved by reducing both ash and sulfur. For example, at the Widows Creek Plant, it was estimated that if ash were to be reduced from 20 to 12 percent and sulfur from 3.5 to 2.0 percent, a plantwide maintenance cost saving of \$1.13/ton (\$1.25/Mg) of coal burned could be achieved (46, 47).

Although the impact of coal preparation on boiler operating costs has not been demonstrated on boilers which burn raw and then cleaned coal, the preponderance of evidence indicates that the reduction in coal ash and sulfur content will in general have a beneficial impact on boiler operations. The difficulty arises in quantifying these cost benefits, since potential reductions in steam-generator costs are dependent on the individual coal properties and the specific boiler design. In some instances cleaning coal may increase its fouling and slagging properties because of selective removal of minerals which will result in an increase in the coal's slagging and fouling index. Fortunately, these conditions probably apply to few coals. In most cases the use of coal cleaning would not only reduce the ash loading but, more importantly, it would also reduce the slagging and fouling potential of the remaining ash (50).

Impact of Coal Cleaning on Power Generation Costs. Perhaps the best method of illustrating the cost benefits of coal cleaning is to present data from case studies of the impact of coal cleaning on power generation.

Table 19-8 presents a comparison of power generation cost components as a function of level-of-cleaning for case B from the 1981 EPRI study (35). These costs are presented in terms of the mean first-year costs given in mid-1978 dollars. Each cost component is presented in terms of three different unit measures: \$/ton of as-fired coal, $\$/10^6$ Btu of as-fired coal, and mills/net kWh of power generation.

Table 19-8. Comparison of Power Generation Cost Components as a Function of Level of Cleaning(35)

	Mean First-Year Costs (1978 $)								
	$/ton as-fired coal			$/$10^6$ Btu as-fired coal			Mills/net kWh		
	Level of Cleaning			Level of Cleaning			Level of Cleaning		
Cost Component	1	2	4	1	2	4	1	2	4
ROM Coal(a)	23.39	27.67	28.00	1.00	1.05	1.04	9.9	10.4	10.25
Coal Preparation	0.93	2.89	4.17	0.04	0.11	0.16	0.4	1.1	1.55
Coal Preparation Refuse Disposal	-	0.35	0.37	-	0.01	0.01	-	0.1	0.15
Prepared Coal (Subtotal)	24.32	30.91	32.54	1.04	1.17	1.21	10.3	11.6	11.95
Coal Transportation(b)	16.50	16.50	16.50	0.71	0.63	0.62	7.0	6.2	6.05
Delivered Coal (Subtotal)	40.82	47.41	49.04	1.75	1.80	1.83	17.3	17.8	18.0
Power Generation(c)	62.15	68.55	69.76	2.66	2.61	2.60	26.25	25.75	25.5
FGD(d)	11.54	12.37	12.31	0.49	0.47	0.46	4.85	4.65	4.5
Power Plant Waste Disposal(e)	2.26	1.63	1.50	0.10	0.07	0.05	1.0	0.6	0.5
Total	116.77	129.95	132.61	5.00	4.95	4.94	49.4	48.8	48.5

(a) Coal source: West Virginia, Logan County, Cedar Grove Seam.

(b) Coal transportation by unit train and collier (1000 miles at 1.65¢/ton-mile).

(c) Power plant location: Quincy, MA.

(d) Limestone FGD.

(e) Includes boiler ash and FGD wastes.

When using \$/ton as a measure, level 1 coal preparation (raw coal) appears to be the least-cost method of power generation. When using \$/10^6 Btu or mills/kWh, level 4 coal cleaning is indicated as being the least-cost method of power generation. In this instance, \$/ton of as-fired coal is an inappropriate measure for making relative comparisons between coal cleaning cases: in cleaning at levels 2 and 4, the coal heating value is enhanced and the amount of coal needed for generation of a fixed amount of power decreases. Multiplying the unit power generation costs by the amount of coal actually burned provides the true rankings:

Level 1: \$116.77/ton x 2.592 x 10^6 tons = \$302.7 million

Level 2: \$129.96/ton x 2.296 x 10^6 tons = \$298.4 million

Level 4: \$132.61/ton x 2.242 x 10^6 tons = \$297.3 million

The ranks remain unchanged if we divide by any appropriate constant; in this case, the amount of raw coal mined and burned at level 1:

Level 1: \$302.7 million ÷ 2.592 x 10^6 tons = \$116.78/ton raw coal (128.75/Mg raw coal)

Level 2: \$298.4 million ÷ 2.592 x 10^6 tons = \$115.12/ton raw coal (\$126.92/Mg raw coal)

Level 4: \$297.31 million ÷ 2.592 x 10^6 tons = \$114.70/ton raw coal (\$126.46/Mg raw coal)

Table 19-9 presents the power plant and transportation costs which are related to the coal cleaning costs given in Table 19-6. The unit costs in Table 19-9 are expressed in terms of relative costs in $/ton. These relative $/ton costs have been adjusted to the level 1 coal mining rate applicable to each case. This provides information on the correct cost ranking for each cleaning option and provides approximate estimates of the relative savings (costs) in $/ton. In four of the five cases in Table 19-9, the use of coal cleaning provides the lowest cost of power generation. In three out of the four cases, level 4 cleaning is the most cost effective and provides for lower costs than does raw coal or coal prepared at level 2. The cost reductions attainable by cleaning ranged from 0.2 to 3.2 percent. In the case where the use of raw coal was the most cost effective approach, level 2 preparation increased net power production costs by 0.4 percent. Level 4 preparation increased power production costs by 0.2 percent. In these last two cases the cost benefits related to reduced transportation, power generation, and FGD costs were not sufficient to offset the increased costs of prepared coal.

The potential cost savings (benefits) which are achieved by coal cleaning in the 1981 EPRI Case B coal to level 2 (B-2) and to level 4 (B-4) are presented in Table 19-10. These potential savings are expressed in $/ton of level 1 coal and mills/kWh. The potential transportation, power generation, FGD waste disposal, and cost savings increase with level of cleaning. The total potential saving for level 2 preparation is approximately $4.71/ton ($5.19/Mg) of level 1 coal or more precisely

Table 19-9. Relative Unit Power Generation Cost Components in $/ton of Level 1 Coal[(a,b)]

Case/Coal	Cleaning Level	Prepared Coal Cost	Power Plant Site (Mileage)[(c)]	Transportation Cost	Power Plant Cost	FGD Cost	Waste Disposal Cost	Total Power Generation Cost
A. IL, No. 6	1	22.17	Glasford, IL (160)	3.00	47.02	13.27	2.39	87.85
	2	24.30		2.83	46.51	12.92	2.05	88.61
	4	25.30		2.71	46.05	12.44	1.93	88.43
B. WVA, Cedar Grove	1	24.32	Quincy, MA (1000)	16.50	62.15	11.54	2.26	116.77
	2	27.39		14.62	60.72	10.96	1.44	115.13
	4	28.15		14.27	60.34	10.65	1.30	114.71
C. AL, American & Mary Lee	1	23.16	Dade City, FL (570)	7.75	45.47	10.33	1.90	88.61
	2	24.89		6.99	44.39	9.92	1.52	87.71
	4	26.01		6.11	43.46	9.12	1.17	85.87
D. IA, Lower Ford	1	20.14	Panora, IA (160)	3.00	46.36	18.47	3.02	90.99
	2	21.56		2.94	46.21	17.61	2.34	90.66
	4	23.72		2.89	46.06	16.48	1.91	91.06
E. UT, Rock Canyon, Gilson, & Sunny Side	1	20.15	Delta, UT (180)	3.00	54.86	9.68	1.12	88.81
	2	22.12		2.52	53.16	9.05	0.74	87.59
	4	22.91		2.42	52.62	8.77	0.61	87.33

(a) Data adapted from Reference 35.

(b) All costs adjusted to annual coal rate at level 1. Annual coal rates are presented in Table 19-6.
Example: Case A, adjusted prepared coal cost for level 4 = $27.99/ton x (2,820,000 tpy/3,120,000 tpy) = $25.30/ton.

(c) Transportation distance from preparation plant to power plant.

Table 19-10. Potential Coal Cleaning Cost Savings for Case B[a]

Cleaning Level/ Cost Component	Potential Cost Savings Relative to Level 1			
	$/ton raw coal[b]	percent reduction[c]	mills/ kWh	percent reduction[c]
Level 2				
Coal transportation	1.88	11.4	0.80	11.4
Power generation	1.43	2.3	0.50	1.9
FGD	0.58	5.3	0.20	4.1
Waste disposal	0.82	36.3	0.40	40.0
Total savings	4.71	5.1[d]	1.90	4.9[d]
Level 4				
Coal transportation	2.23	13.5	0.95	13.6
Power generation	1.81	2.9	0.75	2.9
FGD	0.89	7.7	0.35	7.2
Waste disposal	0.96	42.5	0.50	50.0
Total savings	5.89	6.4[d]	2.55	6.5[d]

(a) Adapted from data in Reference 35.

(b) Total savings in $/ton = level 1 cost - adjusted level i cost; adjusted costs are from Table 19-9 where i=2,4.

(c) Component percent reduction = 100 (saving) ÷ (level 1 component cost).

(d) Total percent reduction = 100 (total savings) ÷ (level 1 costs for trans., pwr. gen., FGD, and waste disp.).

1.9 mills/kWh. For level 4 preparation, the potential saving is $5.89/ton (6.49/Mg) of level 1 coal or 2.55 mills/kWh. The percentage reduction in costs as determined by [100 x (cost saving) ÷ (level 1 cost)] is in close agreement when calculated either from the potential savings in $/ton or mills/kWh (see Table 19-10).

The relative value of the transportation, power generation, flue gas desulfurization, and waste disposal cost savings will depend on site specific factors. For example, in the 1981 EPRI study the ranges of potential cost savings for cost components which provide coal cleaning cost benefits were: transportation, 0 to 37 percent; power generation, 0 to 51 percent; flue gas desulfurization, 14 to 56 percent; and waste disposal, 13 to 44 percent (see Table 19-11).

Thus, coal cleaning cost benefits are very site specific and must be used with caution, either in general coal cleaning studies or in specific plant design studies.

Table 19-11. Change in Relative Percentage of Potential Cost Savings with Coal and Power Plant Site Factors(35)

Case	Total Potential Savings mills/kWh	Percentage of Total Potential Savings: Trans.	Pwr. Gen.	FGD	Waste Disp.	Net Benefit (Cost), mills/kWh
A	1.4	7	43	36	14	(0.1)
B	2.55	37	29	14	20	0.9
C	3.0	30	37	20	13	1.5
D[a]	0.8	--	--	56	44	0.1
E	2.15	16	51	19	14	0.7
Average	1.98	18	32	29	21	0.62

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[a] Level 2 cleaning; all others are level 4.

Level 4 cleaning in case D resulted in a net power generation cost increase of 0.1 mills/kWh.

COAL CLEANING FOR SO_2 EMISSION REDUCTION

The relationships between coal resources, coal cleaning, and SO_2 emission regulations are complex. As discussed in the introduction, the quantity and quality of coal reserves vary significantly. There are also a variety of coal cleaning techniques which can be used, and there are many different SO_2 emission regulations pertaining to the combustion of coal. In assessing the potential uses of coal cleaning for reducing SO_2 emissions, the Clean Air Act and emission regulations which have been promulgated under its mandate will be discussed. Estimates of the gross amounts of coal available for a given emission limit and percentage reduction requirement will then be made. Next, generalizations concerning the uses and limitations of physically cleaned coal (PCC) for compliance with selected emission regulations will be made. Some information on the amount of utility coals which are cleaned will be summarized, and some observations on the cost effectiveness of coal cleaning for reducing SO_2 emissions will be made. The prime question of coal sulfur variability will then be discussed: if an emission limit is not to be exceeded, how much lower than the emission limit must the mean sulfur value of a compliance coal be? Coal washability data and a model of coal sulfur variability will be used to estimate the conditions for which a coal can be expected to comply with SO_2 emission limits over specified averaging times. Finally, sample problems will be presented and solved to show some uses of washability. In this discussion the term "compliance coal" will be used to denote any coal, either raw or cleaned, which can be used to comply with any State or Federal SO_2 emission regulation.

The Clean Air Act

The Clean Air Act of 1970 (P.L. 91-604) and its Amendments of 1977 (P.L. 95-95) provide authority for the U.S. Environmental Protection Agency (EPA) to regulate the discharge of air pollutants into the atmosphere (51, 52). The Act requires EPA to develop and implement regulations designed to limit the quantity of pollutants in the ambient air and to limit pollutant emissions to the atmosphere from stationary and mobile sources. As such, the Act contains several regulatory and enforcement actions for control of emissions from stationary sources using coal. Actions include: (1) creating National Ambient Air Quality Standards (NAAQS) and approving State Implementation Plans (SIPs) to meet these standards, (2) promulgating Federal New Source Performance Standards (NSPS), and (3) establishing national regulations for the Prevention of Significant Deterioration (PSD). A discussion of regulatory activities relating to the Clean Air Act follows.

State Implementation Plans. Under Section 109 of the Act, NAAQS have been established by EPA for sulfur dioxide (SO_2), particulate matter, nitrogen dioxide (NO_2), carbon monoxide (CO), photochemical oxidants, hydrocarbons (HC), and lead (Pb). To implement the NAAQS, each state develops a detailed plan for attaining and maintaining the NAAQS in all regions of the state. These SIPs, which must be approved by EPA (per Section 110 of the Act), include emission limits, timetables for compliance, and enforcement programs. Pursuant to the 1977 Amendments, the SIPs must also (1) stipulate the implementation of reasonable further progress toward attainment of NAAQS, (2) include a comprehensive emission inventory, and (3) identify a quantified growth allowance. The primary manmade source of SO_2 that affects ambient air quality is the combustion of solid and liquid fuels in stationary sources. Therefore, pre- and post-combustion control of sulfur in power plant fuel is a major tool in each SIP for meeting the NAAQS for SO_2.

SIP limits are designated for attainment and maintenance of NAAQS and are, therefore, tailored to local air quality conditions Lower emission limits are often set for plants located in urban areas, where a high density of sources degrades local air quality, than for plants located in rural (clean air) areas. Where possible SO_2 emission standards are set at levels which will allow the use of local coal. For example, in Pennsylvania the SIP limit for many units located in rural areas near major coal fields is 4.0 lb $SO_2/10^6$ Btu (1720 ng SO_2/J). The SIP limit for units located near urban areas is in the 0.6 to 3.0 lb $SO_2/10^6$ Btu (258 to 1290 ng/J) range. Table 19-12 lists typical SIP SO_2 emission limits for a selected number of states.

Emission averaging times under SIP regulations vary from state to state. Some regulations do not specify averaging times. Others specify hourly, daily, monthly, or yearly averaging times.

Table 19-12. Range of SIP SO_2 Emission Limits for Coal-Fired Boilers in Selected States(53)

	Emission Limit, lb $SO_2/10^6$ Btu[a]	
State	Metropolitan Areas[b,c]	Non-Metropolitan Areas[c]
Alabama	1.2 - 1.8	4.0
Colorado	0.4 - 1.2	0.4 - 1.2
Iowa	5.0 - 6.0	5.0 - 6.0
Kentucky	1.2 - 3.3	5.2 - 6.0
Massachusetts	0.56- 1.1	1.1 - 2.4
Ohio	0.32- 5.6	1.6 - 9.6
Pennsylvania	0.6 - 3.0	4.0
West Virginia	1.6 - 5.1	2.7 - 7.5

(a)For boilers with heat input of approximately 10^9 Btu/hr (1.05 J/hr). Many SIPs differentiate emission limits with respect to size. Large boilers generally have more stringent emission limits than small boilers.

(b)Metropolitan and adjacent areas in the same air basin.

(c)Some states specify emission limits on a county or plant basis, resulting in a range of emission limits.

New Source Performance Standards. All boilers sited within a state must comply with applicable SIP emission regulations. In addition, coal fired boilers of greater than 250 x 10^6 Btu/hr (264 GJ/hr) must comply with either of two Federal standards which apply to new boilers (54, 55). The first NSPS applies to boilers constructed between August 17, 1971, and September 18, 1978. The second NSPS applies to coal-fired power plants for which construction commenced after September 18, 1978. The first NSPS specifies an SO_2 emission limit of 1.2 lb $SO_2/10^6$ Btu (516 ng SO_2/J). The 1977 CAA Amendments required EPA to promulgate emission standards for coal-fired steam generators which "reflect a degree of emission limitation and percentage reduction achievable through application of the best technological system of emission reduction." Accordingly, plants constructed after September 17, 1978, cannot emit more than 1.2 lb $SO_2/10^6$ Btu (516 ng/J) and must reduce potential sulfur emissions from high sulfur coal by 90 percent. If emissions are less than 0.6 lb $SO_2/10^6$ Btu (258 ng SO_2/J), then a 70 percent reduction in potential SO_2 emission is required. Sulfur dioxide emission reduction credits which result from coal cleaning are given on the basis of a 3-month average for sulfur removed at the preparation plant.

The emission limit and percentage reduction requirements of the 1978 NSPS are based on a 30-day rolling average. The 1971 NSPS currently incorporates a compliance test that requires 3 hours to complete. The standard is sometimes interpreted to mean that for every 3 hours the mean SO_2 emission cannot exceed the limit.

Nonattainment Areas. The 1977 Amendments also contain provisions to alleviate air pollution in areas where one or more air pollutants exceed the NAAQS (nonattainment areas). Before construction permits are issued by a state, a reduction in emissions from existing sources must be guaranteed to "offset" emission of nonattainment pollutants from the new source. One means to achieve this reduction without the installation of pollution control equipment is to burn cleaned coal instead of run-of-mine (ROM) coal in existing boilers.

Prevention of Significant Deterioration. Provisions of the 1977 Amendments specify formulation of regulations for prevention of significant deterioration (PSD) in the ambient air quality. These regulations are to preserve the air quality in regions that meet the NAAQS (attainment areas). The Amendments establish allowable increases (increments) above baseline concentrations of SO_2 and total suspended particulate (TSP) for three classes of attainment areas. Increments for the other criteria pollutants must also be established by EPA.

In order of increasing PSD allowable increments, clean air areas are designated as Class I, Class II, or Class III. National parks and national wildlife areas are mandatory Class I areas which cannot be redesignated. All other areas were automatically classified as Class II. A Class II area within a state may be redesignated as Class I or III upon request of the State's Governor, approved by the EPA Administrator.

Class I areas are those in which even small deteriorations in air quality are undesirable. Class II areas are those in which deterioration of air quality accompanying moderate industrial growth would not be considered significant. Class III areas are those in which deterioration not exceeding NAAQS would be permitted to allow concentrated or large-scale industrial development.

The construction of major new sources or the modification of existing sources in attainment areas is subject to the PSD provisions of the Act. These sources must incorporate the best available control technology (BACT) for each pollutant subject to regulation. BACT, which is determined on a case-by-case basis, must consider the available technologies and their energy, environmental, and economic impacts. BACT must be at least as stringent as the NSPS for that category of sources. In some instances where higher levels of control are desired, combinations of technologies such as flue gas desulfurization and physical coal cleaning (FGD + PCC) may be required.

Control Trading. Control trading is a generic term EPA uses to describe a number of different market-based approaches which are being studied as possible methods of controlling air pollution in accordance with provisions of the Act (56). It covers offsets, bubbles, netting, and banking of pollution reduction credits for future use. The objective of control trading is to facilitate economic savings in pollution control measures which are taken to meet the PSD and nonattainment provisions of the Act.

Control trading allows emission reductions at one source to be credited to emission control requirements at another source. "Bubbles" are emission trade-offs between existing sources controlled under SIP requirements. "Offsets" are reductions in emissions from existing sources which must be obtained before a new source can be constructed in a nonattainment area. "Netting" applies only to modifications that lead to emission increases at existing sources. By the use of netting, the requirements of a new source review can be avoided by reducing emissions at other nearby existing sources. While the bubble allows existing sources to reduce their costs of control, the offset and netting programs serve an analogous function for new or expanding sources by allowing them to locate in nonattainment or PSD areas without violating ambient air quality restrictions.

In many cases coal cleaning can be used for control trading transactions to provide emission reduction for other new, modified, or existing sources.

Other Applications. Provisions of the Act authorize research on prospective environmental problems. Under these provisions research is being conducted to evaluate the causes and effects of acid rain. Research is also being conducted on alternative means of controlling potential manmade precursors of acid rain. This research includes assessment of the techniques and costs of reducing SO_2 emissions from coal combustion. Coal cleaning is a major technology under consideration for reducing SO_2 emissions from existing power plants.

SO_2 Emission Regulations

There are a number of components to an emission regulation. A regulation may include an emission limit, a percentage reduction requirement, a time period of compliance, the number of times the emission limit may be exceeded, and the technical methods required for demonstrating compliance. The emission limit may be expressed in various terms: pounds per million Btu of heat input, parts per million (ppm) of flue gas concentration, pounds per ton of material processed, pounds per hour of pollutant emitted, etc. (53, 54, 55). The percentage reduction requirement can be expressed in any of the terms used in specifying the emission limits; e.g., a percentage reduction in flue gas concentration or pounds of SO_2 per million Btu. The time of compliance or time period over which the emission limit or percentage reduction is averaged may range from instantaneously to yearly averages. In some cases it is not specified.

The technical method of demonstrating compliance may include the use of coal sampling and combustion calculations, the use of stack sampling techniques, or the use of continuous instrumental emission monitors.

All of the components of the emission regulation influence or constrain the use of a given coal and the technological methods used for producing a compliance fuel. The major constraints are a consequence of the average fuel properties, the technologies used to provide average reductions in emissions, and the time-varying coal properties which may cause the emission limit to be exceeded.

To simplify the discussions which follow, the emission limits and percentage reduction requirements shall be expressed in terms of the heat specific SO_2 emission parameter (pounds of SO_2 per million Btu).

Potential Supply of Compliance Coals

Estimates have been made of the amounts of coal which can be used to comply with various emission limits and percentage reduction requirements. These estimates use coal washability data and projected data on coal production in 1985 (7, 36).

Emission Limits. Figure 19-10 illustrates the amounts of compliance coal which can potentially be produced by the state of Ohio in 1985. The figure contains curves for raw coal and three levels of cleaning. The first level of physical cleaning, designated PCC-1, corresponds to crushing coal to a 1-1/2 inch (37.5 mm) top size and taking a clean coal float product at 1.6 s.g. This is a good estimator for the level of coal desulfurization which can be achieved in commercial coal preparation plants. The second level of cleaning, PCC-2, corresponds to crushing to 3/8-inch (9.5 mm) and taking a clean coal float product at 1.3 s.g. PCC-2, which generally overestimates the potential sulfur emission reductions which can be achieved by modern coal preparation plants, can be used to designate the upper limit of commercially available technology. The third level of cleaning, called Gravichem, is a combined physical/chemical process. It removes approximately 90 percent of the pyritic sulfur but none of the organic sulfur. It can also be assumed to represent the upper limit of advanced physical processes for cleaning fine coal.

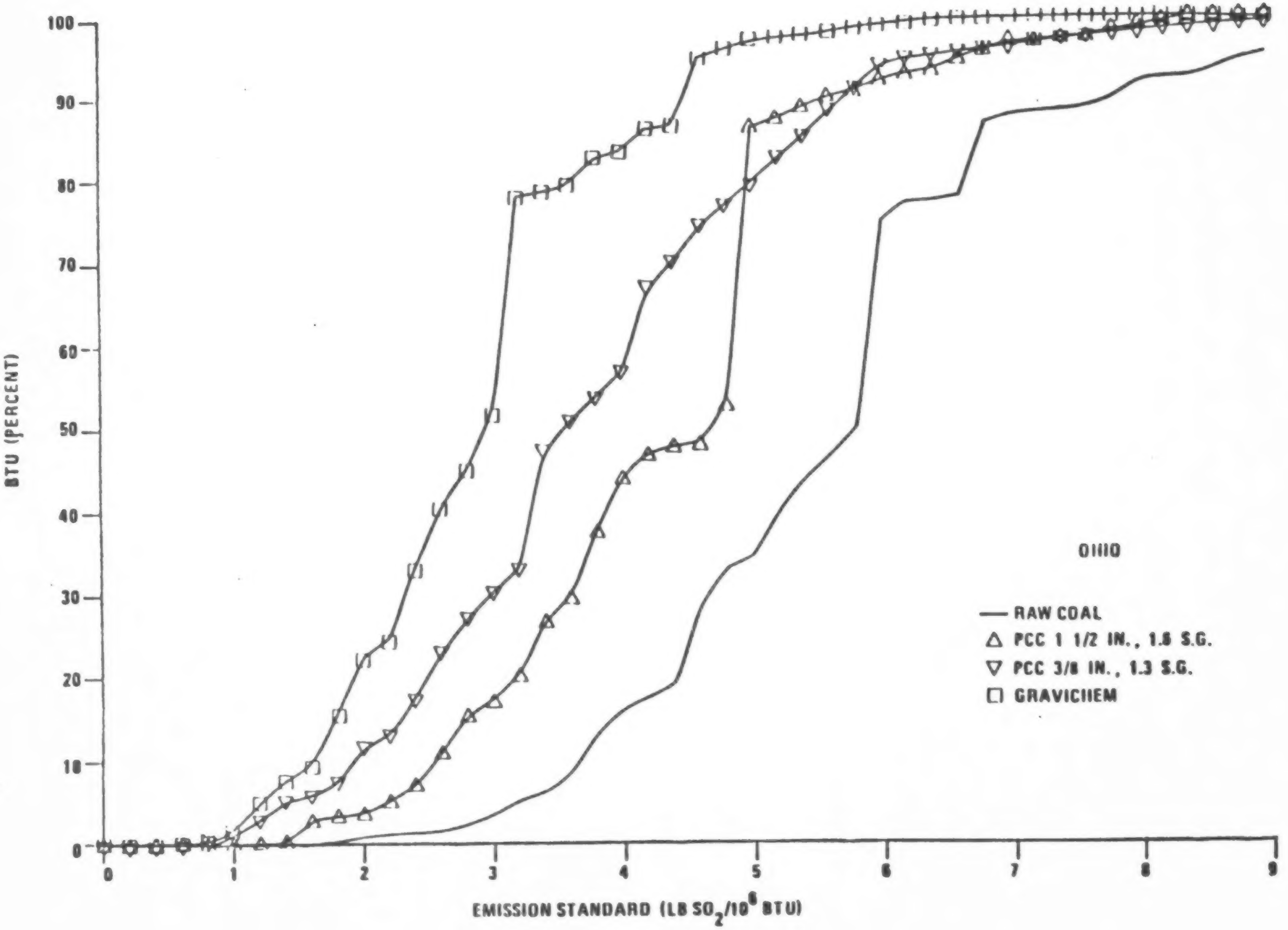


Figure 19-10. Projected 1985 Coal Production in Ohio Able to Meet Various Emission Limits (Total Projected 1985 Coal Production = 1.34 Quads)(7)

Figure 19-10 shows that for all emission limits above 2.0 lb $SO_2/10^6$ Btu (860 ng/J) the amounts of compliance coals increase with the level of cleaning. Also, the amounts of compliance coals increase with increasing emission limit. For example, 17 percent of the raw coal (Btu basis) is capable of complying with an emission limit of 4.0 lb $SO_2/10^6$ Btu (1720 ng/J). By cleaning the raw coal which does not satisfy the 4.0 lb $SO_2/10^6$ Btu (1720 ng/J) emission limit at PCC-1 conditions, a total of 43 percent of the coal produced in Ohio can be made available for compliance with the 4.0 lb $SO_2/10^6$ Btu (1720 ng/J) limit. The amounts available when cleaned at PCC-2 or Gravichem increase to 58 and 82 percent, respectively. At an emission limit of 6.0 lb $SO_2/10^6$ Btu (2579 ng/J), the availability of compliance coals under different scenarios are: raw coal, 75 percent; PCC-1 coal, 92 percent; PCC-2 coal, 95 percent; and Gravichem coal, 99 percent.

The shape of the compliance coal distribution curves for other states which produce high sulfur coals is similar to the Ohio distribution curves.

The compliance coal distribution curves for states producing predominantly low sulfur coals are different from those which produce high sulfur coals. Figure 19-11 presents data on the potential distribution of compliance coals produced in Southern West Virginia. These distribution curves are similar to those from other states which produce only low sulfur coals. The potential sulfur emissions from these coals are low either before or after cleaning. Under different scenarios for

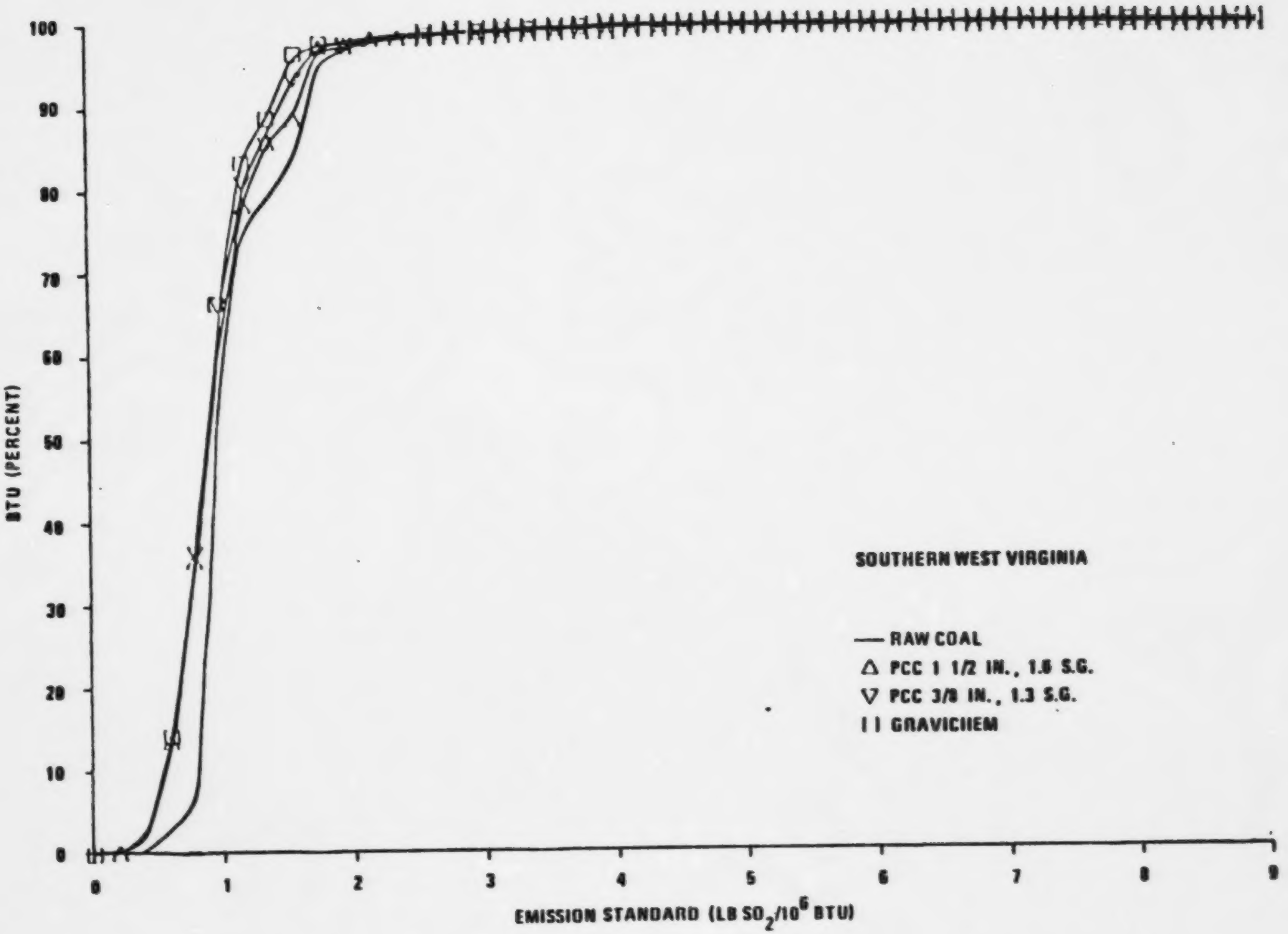


Figure 19-11. Projected 1985 Coal Production in Southern West Virginia Able to Meet Various Emission Limits (Total Projected 1985 Coal Production = 2.42 Quads)(7)

using the Southern West Virginia coal for meeting an emission limit of 1.2 lb $SO_2/10^6$ Btu (516 ng/J), 75 percent of the raw coal, 78 percent of the PCC-1 coal, 80 percent of the PCC-2 coal, and 83 percent of the Gravichem coal produced can be used as compliance fuels. More than 98 percent of all raw and cleaned coals are available in compliance with an emission limit of 2.0 lb $SO_2/10^6$ Btu (860 ng/J).

Table 19-13 provides estimates of the 1985 coal production which can be used to comply with SO_2 emission regulations of 1.2, 2.0, and 4.0 lb $SO_2/10^6$ Btu (516, 860 and 1720 ng/J). These estimates are aggregated at the state, regional, and national levels and are presented for raw coal and one level of physical cleaning (PCC-1). Approximately 34 percent of the uncleaned coal can be used for compliance with an emission limit of 1.2 lb $SO_2/10^6$ Btu (516 ng/J). When cleaned the potential availability of 1.2 lb $SO_2/10^6$ Btu (516 ng/J) compliance coal increases to 43 percent. Most of these raw or cleaned compliance coals come from the low sulfur coal producing states in the Southern Appalachian, Alabama, or Western coal regions. In states in which high sulfur coals predominate, the percentage of raw compliance coals is small for emission limits less than 4.0 lb $SO_2/10^6$ Btu (1720 ng/J). Cleaning of these coals substantially increases the amounts of compliance fuels for emission limits of 4.0 lb $SO_2/10^6$ Btu (1720 ng/J) and above.

Percentage Reduction Requirements. Percentage reduction requirements impose a significant constraint on the production of compliance coals by cleaning. This constraint is more severe for low sulfur coals than high

Table 19-13. Percentage of Projected 1985 Coal Production Able to Meet Selected Emission Limits Using Raw Coal or Cleaned Coal(7)

Region	State(a)	1985 Production (10^6 ton)	Raw Coal Emission Limit (lb $SO_2/10^6$ Btu) 1.2	2.0	4.0	Clean Coal(b) Emission Limit (lb $SO_2/10^6$ Btu) 1.2	2.0	4.0
1	OH	54.5	0	1	16	0	4	43
	PA	99.6	5	20	79	15	48	88
	WV-N	52.8	19	26	62	23	42	81
	TOTAL	209.7	8	17	59	13	35	75
2	KY-E	106.2	49	85	94	58	88	96
	VA	46.4	67	87	100	67	87	100
	WV-S	88.0	75	99	99	78	97	99
	TOTAL	249.6	61	89	97	66	90	98
3	AL	32.1	45	71	93	49	77	94
	TOTAL	32.1	45	71	93	49	77	94
4	IL	92.6	0	7	25	1	16	39
	IN	30.6	6	11	42	10	15	51
	KY-W	58.7	0	0	7	0	0	26
	TOTAL	181.9	1	6	22	2	11	37
5	TX	66.3	0	28	85	1	32	86
	TOTAL	79.2	2	27	69	3	30	76
6	CO	38.0	89	100	100	95	95	100
	MT	75.0	29	100	100	81	100	100
	MN	39.2	53	72	100	54	95	100
	ND	43.8	12	67	100	66	99	100
	UT	33.6	82	99	100	82	99	100
	WY	241.9	46	97	99	54	97	99
	TOTAL	490.6	48	93	100	65	98	99
TOTAL U.S.		1243.1	34	62	74	43	68	84

(a)States producing less than 20 tons not listed but included in totals: MD, GA, TN, AR, IA, KS, MO, OK, AZ, WA.

(b)PCC estimates based on cleaning by crushing to 1-1/2 in. top size and separating at 1.6 s.g.

sulfur coals. Figure 19-12 illustrates the impact of percentage reduction requirements on the potential production of Ohio coals in 1985. Curves in Figure 19-12 are for coals which have been cleaned by PCC-1 and which are subject to a percentage reduction requirement and no emission limit or an emission limit of 3.0, 4.0, 5.0, or 7.0 lb $SO_2/10^6$ Btu (1290, 1720, 2150, or 3009 ng/J). Below a percentage reduction requirement of approximately 15 percent, the emission limit is the primary constraint on the availability of compliance coals. For example, at a percentage reduction requirement of 10 percent there are only marginal reductions in the amounts of available compliance coal as compared with a standard without a percentage reduction requirement. Above 15 percent, the percentage reduction requirement becomes more restrictive and all curves converge for percentage reduction requirements greater than 45 percent. No compliance coals are available in Ohio for PCC-1 cleaning conditions when the percentage requirement is 55 percent or greater. While other data show that higher levels of physical cleaning increase the amount of coal at most percentage reduction requirements, advanced physical cleaning techniques are capable of producing only small amounts of compliance coals at reductions above 70 percent. None can be produced for reduction requirements greater than 90 percent.

The impact of percentage reduction requirements on the availability of compliance fuels in low sulfur coal states is more severe. Figure 19-13 illustrates the effects of percentage reduction requirements and emission limits on the availability of cleaned compliance coals from Southern West Virginia. At an emission limit of 2.0 lb $SO_2/10^6$ Btu

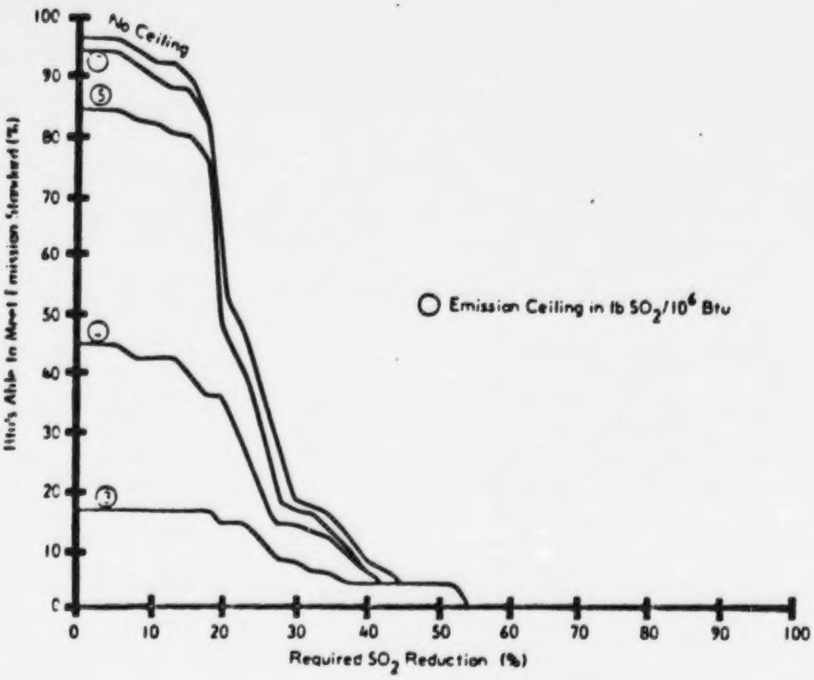


Figure 19-12. Percentage of Projected 1985 Ohio Coal Production Able to Meet Various SO_2 Emission Standards Defined by an Emission Ceiling and Percentage SO_2 Reduction Using Physical Coal Cleaning at 1-1/2 in., 1.6 s.g.(36)

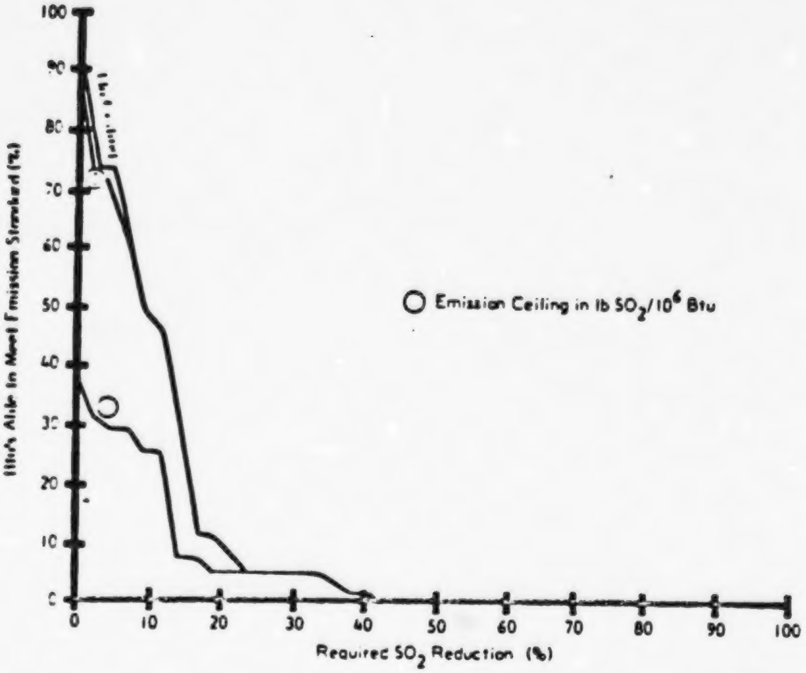


Figure 19-13. Percentage of Projected 1985 Southern West Virginia Coal Production Able to Meet Various SO_2 Emission Standards Defined by an Emission Ceiling and Percentage SO_2 Reduction Using Physical Coal Cleaning at 1-1/2 in., 1.6 s.g.(36)

(860 ng/J), more than 98 percent of the coal can be used as compliance coal. Specifying a percentage reduction requirement causes the availability to fall off precipitously. Compliance coal availability at a 10 percent reduction requirement is approximately 50 percent of the total projected production. At a 20 percent reduction requirement the availability has fallen to approximately 20 percent. There are virtually no compliance coals available for percentage reduction requirements above 45 percent, even at the highest level of physical cleaning represented by removal of 90 percent of the pyritic sulfur. The effects of sulfur reduction requirements on the availability of compliance coals are similar for all low sulfur coal states.

Generalizations on Compliance Coal Availability. In evaluating available data on the desulfurization of coal, the following general observations can be made:

- Physically cleaned Northern Appalachian and Midwestern coals can be used to meet the moderate emission limits specified for old boilers. However, few of these coals can be cleaned to the 1.2 lb $SO_2/10^6$ Btu (516 ng SO_2/J) level specified by the initial new source standards (1971) for coal-fired steam generators.

- Many Southern Appalachian, Alabama, or Western coals are capable of meeting a long-term emission limit of 1.2 lb $SO_2/10^6$ Btu (516 ng SO_2/J), either before or after cleaning.

- Few physically cleaned high sulfur coals can be used to comply with regulations specifying sulfur emission reductions exceeding 50 percent. The physical sulfur reduction potential of many low sulfur coals falls in the range of 10 to 20 percent.

- Except for a small number of coal seams, emission regulations specifying any combination of emission limits below 1.2 lb $SO_2/10^6$ Btu (516 ng SO_2/J) and sulfur reduction requirements above 30 percent eliminate the use of compliance coals which are produced by commercially available physical coal cleaning techniques.

- Advanced physical cleaning and chemical coal cleaning can be used to remove additional amounts of sulfur from coal. However, few processes are capable of 70 to 90 percent reduction in sulfur emissions required for compliance with the latest new source standards for coal-fired utility boilers.

Cleaning of Utility Coals

Utilities have traditionally used coal cleaning for ash removal. The extent to which utilities are using coal cleaning to comply with SO_2 emission regulations is uncertain. Table 19-14 summarizes the current extent to which electric utilities are using coal cleaning in eight Eastern and Midwestern coal producing states. This data provides estimates of the reduction in potential SO_2 emissions which is achieved by current practices. The information in Table 19-14 was developed

Table 19-14. Current (1979) SO_2 and Potential Reduction by Cleaning Utility Coal from Eight States(36)

Region and State in Which Coal Was Mined	Coal Delivered to Utilities in 1979 (10^3 tons)	Utility Coal Cleaned in 1979 (percent)	SO_2 Content of Coal		Average SO_2 Reduction by Coal Cleaning in 1979 (percent)	Additional SO_2 Reduction by Cleaning All Coal	
			As Mined (10^3 tons)	As Delivered (10^3 tons)		(10^3 tons)	(percent)
Northern Appalachia							
Pennsylvania	47,400	30	2,100	1,860	12	470	25
Ohio	38,300	11	2,750	2,670	3	740	28
Northern West Virginia	31,300	23	1,760	1,690	4	280	16
Southern Appalachia							
Southern West Virginia	17,500	9	300	290	1	30	11
Virginia	13,400	7	280	270	1	30	10
Eastern Kentucky	68,600	22	1,630	1,570	4	260	16
Eastern Midwest							
Western Kentucky	38,100	34	2,880	2,600	10	530	21
Indiana	25,300	52	1,620	1,410	13	180	13
Illinois	49,500	72	3,570	2,780	22	230	8
Alabama							
Alabama	14,600	32	460	440	5	70	17
EIGHT-STATE TOTAL	344,000	33	17,350	15,580	10	2,850	18

through use of a 1979 deliveries-to-utilities data and a coal washability data base (36). The deliveries-to-utilities data base specifies the SO_2 content of the as-delivered coal and the quantity of coal cleaned prior to delivery. These specifications were converted to the as-mined qualities and SO_2 contents presented in Table 19-14 by assuming that the washability characteristics of the coals washed prior to delivery were the same as those of the coals that were not washed prior to delivery. For example, a 21 percent SO_2 reduction can be achieved by washing Alabama coals. Therefore, it was assumed that the washed Alabama coals delivered to utilities had had their SO_2 content reduced by 21 percent in the washing process, and that, accordingly, the as-mined SO_2 content was equal to the as-delivered SO_2 content divided by 0.79 (i.e., 1-0.21). Coal weight prior to washing was calculated in a similar manner.

The amount of coal cleaned varies from state to state. Table 19-14 shows, for example, that over half of the coal from Indiana and Illinois and about one-third of the coal from Pennsylvania, Western Kentucky, and Alabama was cleaned prior to delivery to utilities in 1979. This cleaning resulted in significant SO_2 reductions. On the other hand, only small percentages of the coal from Ohio, Virginia, and Southern West Virginia was cleaned prior to utility use in 1979.

The SO_2 reduction that could have been achieved if all coal delivered to utilities in 1979 had been cleaned at 1-1/2 inch (37.5 mm) top size and 1.6 specific gravity (i.e., moderate cleaning) is also summarized in Table 19-14. About 1.7 million (1.5 million Mg) tons more of SO_2 could have been removed in 1979 by cleaning all the utility coal from Pennsylvania, Ohio, and Western Kentucky. Moderate additional reductions in SO_2 emissions could have been achieved by washing other Northern Appalachian and Eastern Midwest coals. By washing all of the utility coals from these eight states, the SO_2 emission from combustion of these coals would have been reduced by 18 percent.

Cost Effectiveness

An evaluation of the cost effectiveness of using coal cleaning for reducing SO_2 emissions must be based on requirements of the various regulations. The most cost effective emission control method is generally that which will satisfy all emission requirements and minimize the cost of power production. Three different types of regulations are of interest: SIP regulations, NSPS regulations, and other regulations such as those which are being advocated for the control of acid deposition.

SIP Regulations. Where SIP regulations specify moderate emission limits, the lowest cost strategies may be the use of uncleaned low sulfur coal, the blending of low and high sulfur coals, the use of physically cleaned coals, or combinations of these strategies. Selection of the lowest cost strategies must include all site specific factors including delivered coal cost (raw and cleaned), transportation costs, coal/boiler compatibility and cost benefits which may accrue from the use of cleaned coals.

These strategy studies must necessarily consider many potential coal supply and cleaning options in arriving at the least cost compliance method. If a strategy involving coal cleaning is the least cost option, then it is the most cost effective.

NSPS Regulations. NSPS may require either a 1.2 lb $SO_2/10^6$ Btu (516 ng/J) emission limit as specified by the 1971 standard for coal fired steam generators, or an emission limit and percentage removal requirement as specified in the 1979 revisions applicable to coal fired electric utility boilers. In the case of the 1971 standard, low sulfur coal and physically cleaned coals will provide the least cost option if they can be obtained at a reasonable price. However, in some instances where transportation distances are large, the use of limestone FGD may provide a lower cost option. In these cases studies have shown that combinations of physical coal cleaning and FGD are generally more cost effective than FGD alone (48, 49). In these instances coal cleaning cost benefits more than offset the costs of cleaning.

For the revised NSPS which requires a 70 to 90 percent reduction in potential sulfur emissions, the most cost effective strategy is dependent upon the cost benefits which accrue from the use of physically cleaned coal (see page 63, Cost Benefits). In evaluating studies which have assessed the use of physical coal cleaning and limestone FGD, the following general conclusions can be made.

- For percentage reduction requirements of 70 percent and less, coal cleaning and FGD is generally more cost effective than FGD alone (26, 48, 49). Cost savings related to reduced transportation, FGD, and waste disposal expenses more than offset the costs of cleaning.

- For medium and high sulfur coals with percentage reduction requirements greater than 70 percent, coal cleaning and FGD is the most cost effective strategy only if there are substantial cost savings in transportation and boiler related costs (26, 35, 48, 49). At high percentage reduction requirements, the FGD cost savings from flue bypass and reduced reheat requirements are not sufficiently large to offset a major fraction of the coal cleaning costs.

- For very high sulfur coals (>5.0 percent) combinations of coal cleaning and limestone FGD appear to be the most cost effective strategy. While FGD bypass cost savings are not available, the reduction in FGD costs due to reduced reagents, slurry pumping, and FGD waste disposal requirements are large enough to offset a major portion of the costs of preparation (57).

Note that the above conclusions are based on comparisons of physical coal cleaning and wet FGD systems which employ limestone scrubbing. These same conclusions may not apply to other FGD systems. The FGD cost savings obtained by using cleaned coal may be substantially different for dual alkali scrubbers, lime spray dryers, or other FGD systems. In any event, studies considering all site specific factors which influence the costs of power generation and SO_2 emission control must be made before the most cost effective strategy is selected.

Other Regulations. In studies concerning state, regional, and national strategies, such as those for reducing the emission of acid rain precursors, the use of different emission control technologies are compared in terms of $/ton of SO_2 reduction. The cost effectiveness of alternative control technologies are then compared by the use of this measure. In the case of coal cleaning, the cost effectiveness for SO_2 emission reduction can be expressed as the unit annual coal preparation cost (in $/ton of clean coal) divided by the potential reduction in SO_2 emissions expressed as the tons of SO_2 reduction per ton of clean coal. Alternatively, it can be expressed as the annual costs of preparation divided by the annual reduction in SO_2 emissions. The cost effectiveness for cleaning is, therefore, a function of the coal preparation cost, the original sulfur content and washability of the coal, and the cleaning level employed. It is most sensitive to the original sulfur level and the washability. It is also dependent upon any cost benefits which may result from cleaning. Not surprisingly, coal cleaning cost effectiveness varies from coal to coal. The cost effectiveness for cleaning high sulfur coals is quite different from that for cleaning low sulfur coals.

The cost effectiveness of cleaning Ohio and southern West Virginia coal is compared in Table 19-15 (36). These comparisons correspond to

Table 19-15. Potential SO_2 Emission Reductions and Costs Due to Selective Cleaning of Ohio and Southern West Virginia Coals Delivered to Utilities in 1979 (36)

Coals To Be Cleaned	Quantity To Be Cleaned (10^3 tons)	Total SO_2 Emissions after Selective Cleaning (10^3 tons)	SO_2 Emission Reduction Achieved by Selective Cleaning (10^3 tons)	SO_2 Emission Reduction Achieved by Selective Cleaning (%)	Levelized Cost of Cleaning[(c)] (10^6 1979 $)	Cost-Effectiveness ($/ton SO_2)
Ohio						
No coals(a)	0	2,479	0	0	0	-
Coals with SO_2 contents above floor of:						
7 lb/10^6 Btu	12,353	2,101	378	15	137	360
6 lb/10^6 Btu	20,225	1,964	515	21	201	390
5 lb/10^6 Btu	27,063	1,832	647	26	273	420
4 lb/10^6 Btu	31,986	1,757	722	29	302	420
All coals	34,527	1,735	744	30	322	430
Southern West Virginia						
No coals(b)	0	267	0	0	0	-
Coals with SO_2 contents above floor of:						
4 lb/10^6 Btu	82	267	<1	<1	<1	-
3 lb/10^6 Btu	337	263	4	2	4	1,000
2 lb/10^6 Btu	933	260	8	3	8	1,000
1 lb/10^6 Btu	15,677	236	31	12	123	3,970
All coals	16,013	236	31	12	126	4,060

(a) Excludes 3,787,000 tons of Ohio coal actually cleaned in 1979.

(b) Excludes 1,450,000 tons of Southern West Virginia coal actually cleaned in 1979.

(c) Levelized costs 1.178 times higher than the first year annualized costs.

SO_2 emission control scenarios which require that all coals which were not washed and which have SO_2 emission potentials greater than a given floor level be washed. As the floor level decreases the cost effectiveness of cleaning all the previously unwashed coal increases. This results from the fact that smaller amounts of sulfur are being removed from the lower sulfur coals while the costs of cleaning remain nearly constant. In Ohio, which contains high sulfur coals, the levelized cost effectiveness of cleaning ranges from \$360/ton to \$430/ton (\$397/Mg to \$474/Mg) SO_2 removed. In Southern West Virginia the cost effectiveness of cleaning ranges from \$1000/ton to \$4060/ton (\$1102/Mg to \$4476/Mg) of SO_2 removed. These values for cost effectiveness are typical of those given in Reference 36 for cleaning coals from other high and low sulfur coal states. Note that these values can be substantially reduced by accounting for coal cleaning cost benefits.

Sulfur Variability

Many boiler operators attempt to comply with SO_2 emission regulations by using low sulfur coal, blends of low and high sulfur coals, or physically cleaned coal. However, the sulfur and heating value of coal may vary significantly with time, and it is difficult to ensure that a "compliance coal" will indeed satisfy conditions of the emission regulation for which it was purchased.

Emission regulations generally specify an emission limit and an averaging time. Average pollutant emissions during this time period are not to exceed the limit. The ability of a coal to comply with an emission regulation depends on the statistical characteristics of the coal sulfur and ash, the requirements of the regulation, and the rate at which coal is burned (boiler size).

Sulfur emissions from coal combustion vary in time in a probabilistic manner. There is also some structure to the sulfur emissions. If the sulfur emissions were high 1 hour ago, it is likely that they are high now.

The sulfur and ash content of coal varies vertically and laterally within a coal seam. Lines of constant sulfur representing the average sulfur content at a given location can be drawn on the map of a coal mine in a manner similar to lines of constant elevations on a contour map. The sulfur content of individual coal particles at any mine location may vary randomly around the average value for that location.

Mining of the coal transforms its spatial properties into a unique time sequence of potential sulfur emissions. This time sequence of potential sulfur emissions is dependent upon the mining scheme--a different mining scheme will produce a different series of potential sulfur emissions. Blending, coal preparation, coal transportation, and boiler pollution control devices will modify and attenuate the variability of the "as-mined" coal (58).

Importance of Sulfur Variability. The importance of coal sulfur variability can best be illustrated by examining some data which show the variability of potential sulfur emissions in time. Figure 19-14 is a plot of the sulfur emission parameter (lb $SO_2/10^6$ Btu) for raw and cleaned coal data from the Kitt Mine preparation plant in West Virginia (58).

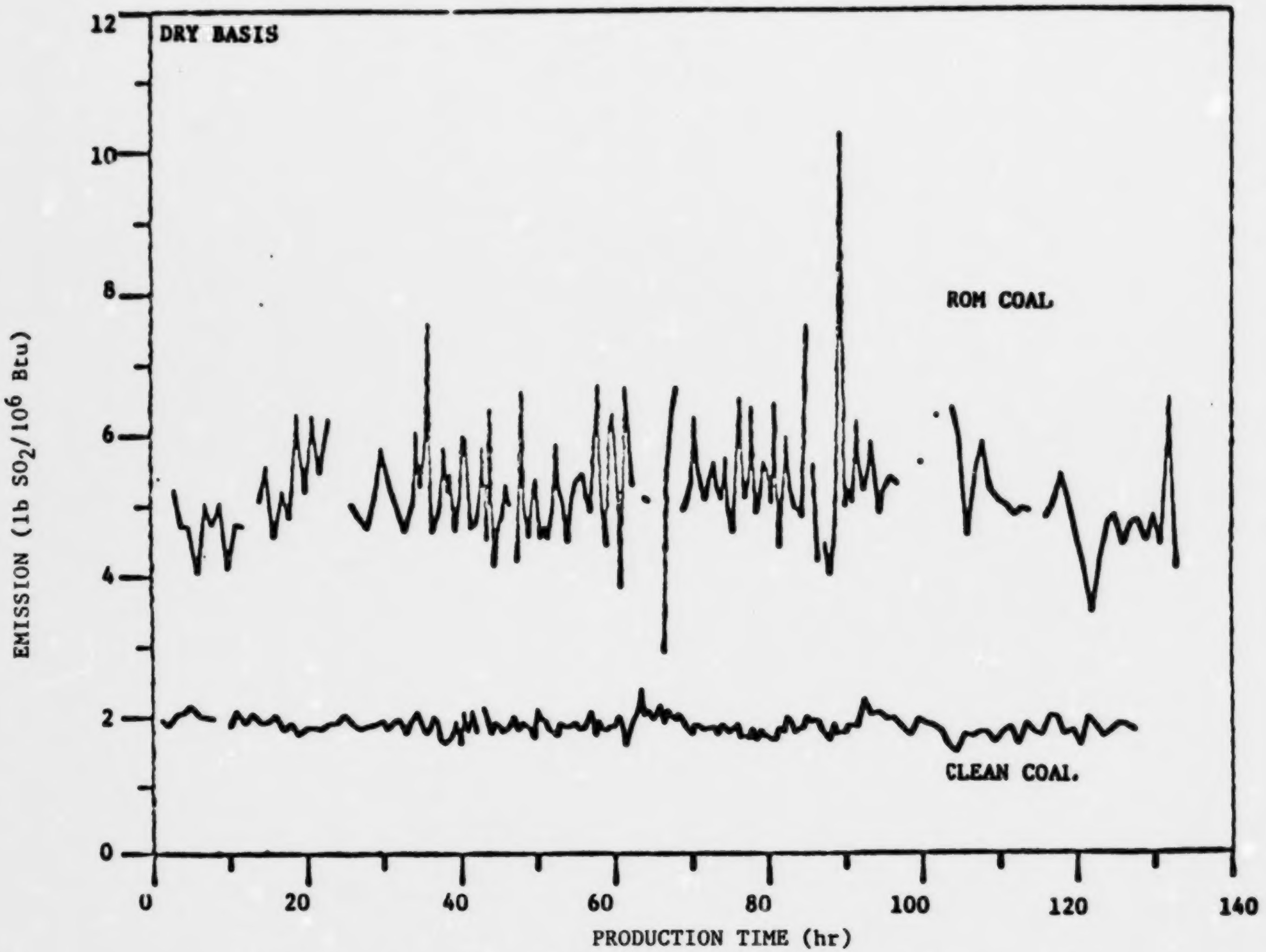


Figure 19-14. Kitt Mine Coal Preparation Plant - Hourly Incremental Data for Sulfur Dioxide Emission Parameter(58)

Each raw coal data point represents the average emission which would result from burning 800 tons (726 Mg) of coal. Each raw coal data point is said to represent a lot size of 800 tons (726 Mg). Each clean coal data point represents a lot size of 460 tons (417 Mg).

Under typical conditions an 80 MW boiler may burn approximately 800 tons (726 Mg) of coal in 24 hours. It is assumed that the Kitt Mine raw coal must be used to comply with an emission limit incorporating a 24-hour averaging time, the amount of coal represented by each hour of production (one data point). It is seen from Figure 19-14 that the maximum emission average for 1 hour of production is greater than 10 lb $SO_2/10^6$ Btu (4299 ng SO_2/J). Many of the 1-hour production averages and hence many of the 24-hour emission averages are above 5.5 lb $SO_2/10^6$ Btu (2364 ng SO_2/J). The mean raw coal sulfur emission for the entire 140 hours of production would be 5.2 lb $SO_2/10^6$ Btu (2236 ng SO_2/J). The raw Kitt Mine coal could be used to comply with a 5.5 lb SO_2/10 (2364 ng SO_2/J) emission standard if the regulation specified a 140-day averaging time instead of a 24-hour averaging time.

An obvious conclusion is that emission regulations which incorporate short averaging times are more difficult to comply with than those with long averaging times. In the same manner, it is easier for large boilers to comply with a given emission limit than small boilers. In 1 hour a 500 MW boiler will burn 20 times more coal than a 25 MW boiler. A 1-hour averaging time for a 500 MW boiler would be equivalent to a 20-hour averaging time for a 25 MW boiler since equal amounts of coal would be burned during these time periods. Long term emission averages or large lot size averages are always less than or equal to the maximum values of the smaller incremental averages which they comprise.

The variability of cleaned coal sulfur emissions is much less than that for raw coal. The maximum emissions from the hourly production of cleaned Kitt Mine coal were approximately 2.25 lb $SO_2/10^6$ Btu (967 ng SO_2/J), a factor of 4.4 less than the maximum potential emission from the raw coal.

In some instances emission limits are defined as maximum values which are never to be exceeded under penalty of law. In other cases, standards are interpreted to mean that the maximum emission as determined by the compliance test method is never to exceed the emission limit. These are stringent requirements where continuous emission monitors and/or 3-hour stack emission tests are employed to determine compliance. These difficulties can largely be mitigated by regulations which specify 24- or 30-day averages.

Some state, county, or municipal air pollution authorities enforce sulfur emission regulations on the basis of short averaging times. It is, therefore, important to understand the relationship between the maximum and average SO_2 emissions, and various types of SO_2 emission standards. To aid in enforcement and to ensure that the short term ambient air quality standards (3-hour average) are met, it is desirable to develop methods for specifying mean coal sulfur emission parameter values which should not be exceeded. These determinations must be based upon the statistical characteristic of coal sulfur emissions.

Definition of Statistical Terms. Mean value, variance, standard deviation, relative standard deviation, and autocorrelation are terms used to evaluate coal sulfur variability. The mean value, μ, is simply the large sample average which is estimated by the sum of all values of the variable x divided by the number of data points. The variance is a measure of the data scattered about the mean value. The variance σ^2, is estimated by the sum of the squared distance of each point from the mean divided by an appropriate constant. The standard deviation, σ, is the square root of the variance. The relative standard deviation, RSD= σ/μ, is a normalized form of the standard deviation.

If values in a sequence of data points are dependent upon previous values, then they are said to be autocorrelated. A normalized version of the autocovariance is the autocorrelation. In more detail, ρ_j is the autocorrelation for lag j. It measures the dependence of data separated by j time intervals.

The usefulness of the autocovariance or autocorrelation is in forecasting present and future data from past events. Small autocorrelations may indicate that the relation between past and present values is small so that past data probably provide little useful information in predicting present and future events. If the autocorrelation is large it is essential to determine the time dependent effect through modeling in order to predict future trends. Models which use past values of x to predict present and future values of x are called autoregressive models. The number of past data points needed to discuss future effects is the order of an autoregressive model. Thus with an AR(1) model only the previous data point is useful in forecasting the present. An AR(2) model requires the two previous data points to forecast present conditions. Once these trends have been forecast by time series analysis the variance can be used to provide an estimated measure of their accuracy. The statistical techniques of time related values are called time series analysis (59).

Time Series Model of Emissions. Assuming that all of the coal sulfur is emitted as SO_2 upon combustion, the relationship between the estimated mean coal sulfur emission parameter and a limiting emission value may be expressed by:

$$E_L = \mu (1 + Z_\alpha RSD_n) \qquad \text{Eq. 19-1}$$

where: E_L = time average emission limit for an averaging time, t.

μ = time independent mean emission value for a given coal population. This value of μ will provide an expected exceedance rate of α (i.e., α is the average allowable proportion of the averaging periods during which the emission standard may be exceeded).

Z_α = normal percentile (percentage) point corresponding to an expected exceedance rate α. For Z_α = 1 it is expected that emissions will on the average be exceeded 15.9 percent of the averaging periods. For Z_α = 1.5, 2.0, and 2.5 the average expected exceedances are 6.7, 2.3, and 0.6 percent, respectively.

RSD_n = a relative standard deviation for a time sequence of n reference lots of size ℓ such that n lots are burned during the emission averaging time of E_L. The total lot size (weight) for n reference lots is $L=n\ell$.

The values of parameters in Eq. 19-1 must be estimated using coal sampling and analysis (CSA) data. The method for estimating these parameters is summarized below. A discussion of application of the model follows the discussion of mathematical development.

Mathematical Development of Model. The coal statistical parameters must be estimated using CSA data. The major parameter to be estimated is RSD_n. An estimated value of a parameter will be designated by placing a "hat" over the symbol; e.g., $\widehat{RSD}_n$.

RSD_n is a measure of the variability of coal lots of size L. This variability is a function of the lot size and autocorrelation structure. Previous studies have shown that the RSD_n can be expressed by:

$$RSD_n = \frac{RSD_1 \cdot \omega_n}{\sqrt{n}} \qquad Eq\ 19\text{-}2$$

where: RSD_1 = the RSD for all reference lots of size ℓ corresponding to n=1.

ω_n = a function of the autocorrelation function for n reference lots with autocorrelation structure ρ_n.

n = number of reference lots in ℓ.

As noted, RSD_1 is a measure of the sulfur variability between reference lots of size ℓ and is explicitly dependent on errors in CSA data. CSA data must be used to estimate RSD_1, and limitations of current CSA data sets make it impossible to separate errors related to the CSA process from the inherent variation in coal properties. Since overestimation of the variability will lead to a conservative result, it is reasonable to use an estimation of RSD_1 which is obtained by:

$$\hat{RSD}_1 = \frac{1}{\bar{X}_N}\left[\sum_{i=1}^{N}\frac{(X_i-\bar{X}_N)^2}{N-1}\right]^{1/2} \qquad \text{Eq. 19-3}$$

Where: $\bar{X}_N = \sum X_i / N$, and X_i is the value of each of N independent values of x. In general, this estimation will include variability terms related to the variance between the reference lots, the variance of the coal samples within the reference lots (a representation error), and the variance resulting from the inherent variability in sample preparation and analysis procedures.

The value of ω_n can be estimated from CSA data by the use of time series models. No single time series model has been found which can describe exactly the potential sulfur emission from all coal sulfur data sets. However, the effects of averaging time (n) and autocorrelation can be approximated by an autoregressive model of order 1. For the AR(1) model the function of autocorrelation can be expressed in the simplified form (60):

$$\hat{\omega}_n = \left[\frac{1-\hat{\rho}_1^{\,2}-2\hat{\rho}_1/n+2\hat{\rho}_1^{\,n+1}/n}{(1-\hat{\rho}_1)^2}\right]^{1/2} \qquad \text{Eq. 19-4}$$

Where: $\hat{\rho}_1$ is an estimated value of the autocorrelation at lag 1 as determined from CSA data with the equation:

$$\hat{\rho}_1 = \sum_{i=1}^{N} (X_{i+1} - \bar{X}_N)(X_i - \bar{X}_N) \Big/ \sum_{i=1}^{N} (X_i - \bar{X}_N)^2 \quad \text{Eq. 19-5}$$

The effects of coal sulfur variability on the mean emission parameter which is required for compliance with a given emission regulation may be determined using CSA data and Eq. 19-1 through 19-5. To illustrate the effects of coal statistical parameters on the probable value of μ needed for compliance, it is necessary to identify some representative values of $\widehat{RSD}_1$ and $\hat{\rho}_1$.

Depending on the lot size and other considerations, $\widehat{RSD}_1$ may range from less than 0.7 to greater than 0.35 (58, 61, 62). In one carefully controlled study at the R&F coal preparation plant in Cadiz, Ohio, it was determined that $\widehat{RSD}_1=0.14$ for raw coal reference lots of 428 tons (388 Mg) (58). At the same plant, $\widehat{RSD}_1=0.10$ for cleaned coal reference lots of 330 tons (299 Mg). Using this information, 0.20 and 0.12 can be assumed as reasonable values of $\widehat{RSD}_1$ for raw and cleaned coal (respectively) at a lot size of 240 tons (218 Mg).

The autocorrelation structure of coal has not been studied widely. However, cleaned coal is more highly correlated than raw coal. The cleaning process reduces variability, and properties of adjacent coal lots are more likely to be similar for clean coal than for raw coal. For the R&F plant, the values of $\hat{\rho}_1$ for coal data collected every half hour were about 0.25 for raw coal and 0.50 for cleaned coal. These values of $\hat{\rho}_1$ will be used hereafter for illustrative purposes.

Emission regulations do not normally specify a value for Z_α nor do they identify the percentage of time emissions can exceed the limit without violating the regulation. A value of $Z_\alpha = 2.5$, corresponding to compliance with the emission limit 99.4 percent of averaging periods, will be assumed.

Effects of Variability Parameters on $\hat{\mu}/E_L$. Using equations developed earlier, Eq. 19-1 can be expressed in terms of CSA data:

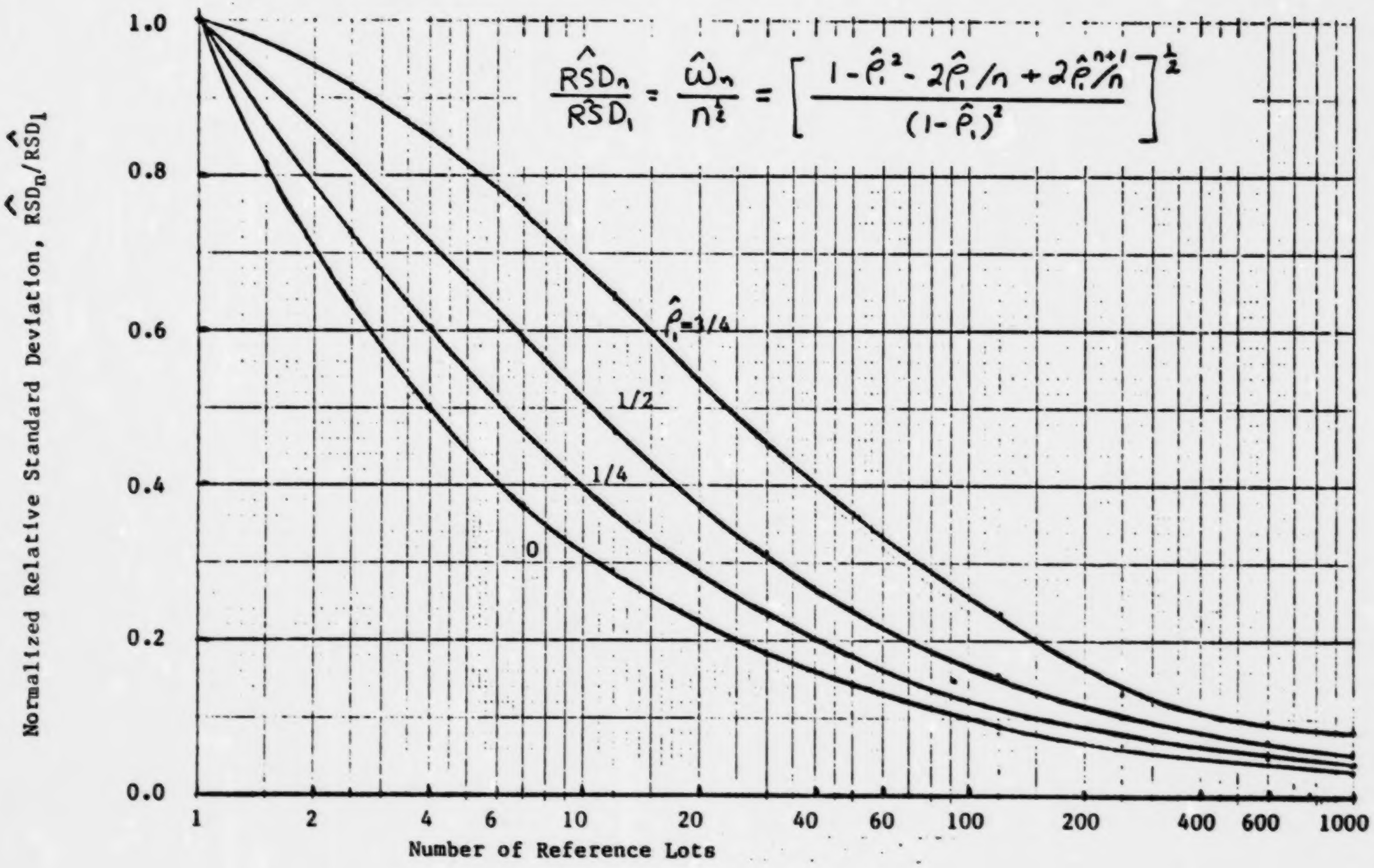
$$\hat{\mu} = \frac{E_L}{1 + Z_\alpha \widehat{RSD}_n} = \frac{E_L}{1 + Z_\alpha \frac{\widehat{RSD}_1}{\sqrt{n}} \hat{\omega}_n} \qquad \text{Eq. 19-6}$$

Where $\hat{\mu}$ is the estimated value of the time independent emission parameter needed for compliance with E_L. As discussed earlier, $\widehat{RSD}_1$ is an estimate of the variability of the reference lots of size ℓ, and $\hat{\omega}_n$ is a measure of the autocorrelation structure of coal samples which are taken to estimate properties of the reference lots.

In the development of Eq. 19-6, it was assumed that CSA data provide an unbiased estimate of the mean coal properties and that all of the coal sulfur is converted to SO_2 during combustion. The factors of sulfur capture and CSA biases were not incorporated in Eq. 19-6 because they may vary significantly from site to site. In actual application these factors must be taken into account.

Model Analyses. An analysis of the effects of n and $\hat{\rho}_1$ on the normalized lot size, $\widehat{RSD}_n/\widehat{RSD}_1$, shows that the averaging of reference lots over successively larger lot sizes significantly attenuates the effects of coal sulfur variability. However these attenuating effects are reduced as autocorrelation increases. The effects of n and $\hat{\rho}_1$ on $\widehat{RSD}_n/\widehat{RSD}_1$ are shown in Figure 19-15. For example, with zero autocorrelation ($\hat{\rho}_1 = 0$) and with a lot size equal to 4 reference lots ($n=4$), the relative standard deviation is decreased to 0.50 times its initial value ($\widehat{RSD}_n/\widehat{RSD}_1=0.5$). For $n=4$ and $\hat{\rho}_1 = 1/2$, the value of $\widehat{RSD}_n/\widehat{RSD}_1$ is 0.71. For $n=600$ and autocorrelations of 0 and 1/2, the values of $\widehat{RSD}_n/\widehat{RSD}_1$ are 0.04 and 0.07, respectively.

The effects of emission averaging time, boiler size, and autocorrelation on $\widehat{RSD}_n$ and $\hat{\mu}/E_L$ are shown by Table 19-16. The total coal lot size is equal to the emission averaging time multiplied by the rate at which coal is fired in a specific size boiler. The raw and clean coal statistical parameters used in Table 19-16 are estimated from coal sample test data discussed earlier. While the cleaned coal generally has a higher autocorrelation coefficient than raw coal, this is offset by a lower value of $\widehat{RSD}_1$ for clean coal. For small boilers and short averaging times, the effects of cleaning in reducing fuel sulfur variability are significant. For large boilers and long averaging times, the difference between raw and cleaned coal is small. For example the mean coal emission parameters required to comply with a



$$\frac{\hat{RSD}_n}{\hat{RSD}_1} = \frac{\hat{\omega}_n}{n^{\frac{1}{2}}} = \left[\frac{1-\hat{\rho}_1^2 - 2\hat{\rho}_1/n + 2\hat{\rho}_1^{n+1}/n}{(1-\hat{\rho}_1)^2}\right]^{\frac{1}{2}}$$

Figure 19-15. Effect of Autocorrelation and Number of Reference Lots on $\hat{RSD}_n/\hat{RSD}_1$

Table 19-16. Effect of Coal Statistical Parameters on Fractional Coal Emission Parameter(a)

No. of Ref. Lots, n	Lot Size, tons	Boiler Size, MW(b)	Averaging Period, hours (days)	Raw Coal(c)		Clean Coal(d)	
				$\widehat{RSD}_n$	$\hat{\mu}/E_L$	$\widehat{RSD}_n$	$\hat{\mu}/E_L$
1	240	25	24(1)	0.200	0.667	0.120	0.769
25(e)	600	500	3(1/8)	0.145	0.733	0.099	0.802
4	960	100	24(1)	0.120	0.769	0.086	0.823
7	1,680	25	168(7)	0.094	0.810	0.071	0.850
20	4,800	500	24(1)	0.057	0.875	0.045	0.899
30	7,200	25	720(30)	0.047	0.895	0.037	0.915
120	28,800	100	720(30)	0.024	0.945	0.019	0.955
600	144,000	500	720(30)	0.011	0.974	0.009	0.979

(a)Based on time series analysis using an AR(1) model and $Z_\alpha = 2.5$.

(b)Coal firing rate = 0.40 tph/MW.

(c)For raw coal reference lot size of 240 tons: $\widehat{RSD}_1 = 0.20$ and $\hat{\rho}_1 = 0.25$. autocorrelation coefficient = 0.25.

(d)For clean coal reference lot size of 240 tons: $\widehat{RSD}_1 = 0.12$ and $\hat{\rho}_1 = 0.50$.

(e)It is assumed that the AR(1) model can be used to estimate the $\widehat{RSD}_n$ for fractional reference lot numbers >1.

4.0 emission limit with alternative averaging times of 24 hours and 30 days in 25 MW and 500 MW boilers are:

	Required $\hat{\mu}$ for E_L=4.0	
	24 hr.	30 days
25 MW, raw coal	2.67	3.58
clean coal	3.08	3.66
500 MW, raw coal	3.50	3.90
clean coal	3.60	3.92

Note that the values of $\hat{\mu}/E_L$ are uniquely determined by $\widehat{RSD}_1$, $\hat{\rho}_1$, and n. The relationship between lot size and averaging time is not defined until a reference lot and a boiler size are defined. Thus the values of $\hat{\mu}/E_L$ as defined by $\widehat{RSD}_1$, $\hat{\rho}_1$, and n may apply to lot sizes, boiler capacities, and averaging periods other than shown in Table 19-16. For example, assume that coal data is obtained for a reference lot size of 960 tons (871 Mg) and that $\widehat{RSD}_1$=0.20 and $\hat{\rho}_1$=0.25. If this coal is to be burned in a 100 MW boiler, then for a 24-hour averaging period n=1 and $\hat{\mu}/E_L$=0.667. This is a lower value of $\hat{\mu}/E_L$ than given in Table 19-16 for a 100 MW boiler, a 24-hour averaging period, and a reference lot size of 240 tons (218 Mg). This lower value of $\hat{\mu}/E_L$ is a consequence of the larger reference lot size. The relationship between boiler size, averaging period, and coal lot size must be adjusted for different reference lot sizes.

Compliance Determinations. Earlier, a coal sulfur variability model was used to illustrate the effects of $\hat{RSD}_1$, n, and $\hat{\rho}_1$ on the value of $\hat{\mu}/E_L$ needed for compliance. In practice, this procedure will be reversed. CSA data will be used to determine if a specific coal complies with a given emission regulation. This can be accomplished as follows.

The values of $\hat{RSD}_1$, $\hat{\rho}_1$, and $\hat{\omega}_n$ can be determined from data collected during the previous weeks of operation. Then if $\bar{X}_n$ is the average emission parameter for any given coal lot size L, $\bar{X}_n$ can be expected to comply with E_L with average exceedances of less than α if:

$$\bar{X}_n \leq \hat{\mu} = \frac{E_L}{1 + Z_\alpha \frac{\hat{RSD}_1}{\sqrt{n}} \hat{\omega}_n} \qquad \text{Eq. 19-7}$$

Note that the model can only be used when coal data is available for coal reference lot sizes which are equal to, or less than, the amount of coal burned during the averaging period; i.e., for $n \geq 1$. If the reference lot size, ℓ, is greater than ℓ there will generally not be enough data to estimate $\hat{RSD}_1$ without additional model assumptions. This fact poses problems when making compliance determinations in small boilers. It would require that the coal and utility industry collect data for smaller reference lot sizes than are customary. This can be illustrated by examining the following limiting reference lot sizes which are required for boilers of various capacities and averaging times.

Boiler Capacity, MW	Limiting Reference Lot Size, tons 3 hours	 24 hours	 30 days
5	6	48	1,440
25	30	240	7,200
100	120	960	28,800
500	600	4,800	144,000
1,000	1,200	9,600	288,000

Compliance determinations by the previously outlined method will generally require additional CSA data for boilers of less than about 100 MW with averaging times less than 24 hours. The coal and utility industries seldom obtain coal data on reference lot sizes smaller than 1000 tons (907 Mg). If CSA data are to be used for compliance determinations for small boilers, then either (1) more sophisticated models must be developed to estimate the statistical properties of small lot sizes, (2) CSA data must be collected for smaller reference lots than is customary, or (3) longer averaging times must be used.

One final observation is appropriate. The variability between lot sizes decreases with increasing lot size. This is not always apparent from CSA data because the proportion of the various components which make up RSD_1 may vary with reference lot size. For small reference lots the variance of properties between lots may be large, but the representation variance (the difference between the coal sample properties and the average properties of the reference lot) may be small. Alternatively, for large reference lots the variance between lots may be small, but the representation variance may be large. The representation variance for large reference lots can be reduced by taking many subsamples from the reference lot to form a single sample for laboratory analysis. The representation variance will then be dependent on the number (frequency) of subsamples and the manner in which the subsamples are collected, composited, and prepared for laboratory analysis. The estimated value of RSD_1 will thus be highly dependent on the CSA procedures used to collect coal data.

Validation and Use of Model. The coal sulfur variability model described here has been shown to provide a reasonable first estimate of the statistical behavior of coal properties in all data sets against which it has been tested. Other coal emission parameters and boiler SO_2 emission data generated by EPA and other organizations agree with the general features of this model. However, insufficient information is known about available coal data sets to allow for a general validation of the model.

In some cases the model may prove inadequate. The model described here does not include the effects of long-term (daily or weekly) autocorrelation effects which are a consequence of specific coal mining or utilization patterns. Coal from many different mines or different mine locations is often fired in the same boiler during the period of a year. These coal use patterns represent a mixing of different coal populations. While the model was shown to apply to the mixed coal populations over a 30-day period at the R&F coal preparation plant (60), it may not apply to mixed populations under other conditions.

Another model may be required for assessing compliance in very small boilers with short averaging times. The frequency of coal sampling required to make compliance determinations with the model presented here may be economically prohibitive.

Federal and State SO_2 emission regulations are not now structured to employ statistical methods for determining compliance with SO_2 emission regulations. The U.S. EPA and some state air pollution control authorities are currently formulating CSA procedures which are to be used for compliance determinations. The models described here to estimate the mean SO_2 emission parameter values needed for compliance will only be valid if the promulgated CSA procedures and the associated emission regulations are based on similar statistical techniques.

In summary, it is emphasized that the mean coal sulfur values needed for compliance must be determined on a case by case basis and must be consistent with regulatory requirements. A simplified model was used here to illustrate the relative importance of reference lot size, averaging time, relative standard deviation, and autocorrelation in estimating the statistical properties of emissions. This model is probably valid for short term daily emission averages with moderately well behaved populations. Other models may be necessary to account for longer term variations in mixed coal populations or for small lots sizes which are burned over short time periods in small boilers.

Estimates of Performance

A complete description of plant design procedures and equipment performance specifications is beyond the scope of this chapter. However, preliminary estimates of the ash and sulfur reductions which can be achieved in coal preparation plants can be made from washability data. The effects of sulfur variability on the level of cleaning needed to produce a compliance coal can also be estimated. The best approach to understanding the use of coal washability data and the effects of coal sulfur variability is to present and solve a number of problems.

Problem 1. A 500 MW utility boiler in Harrison County, Ohio, must comply with a 4.5 lb $SO_2/10^6$ Btu (1935 ng SO_2/J) emission limit. The regulation is based on a 24-hour emission averaging time. A nearby mine in Harrison County is providing cleaned coal under a long-term contract. The mean properties of this coal are those which are given by the washability data in Table 19-2.

The plant is currently designed and operated at Level 2 conditions which are approximated by crushing to 1-1/2 inches (37.5 mm) and separating at 1.6 s.g. This results in a product with a mean sulfur emission parameter of 4.5 lb $SO_2/10^6$ Btu (1935 ng SO_2/J). CSA data collected for cleaned coal at a reference lot size of 1200 tons (1088 Mg) show that $\widehat{RSD}_1=0.10$ and $\hat{\rho}_1=1/2$. (a) Determine the value of the mean SO_2 emission parameter, $\hat{\mu}$, which will provide an expectation that the emission limit is met 99.4 percent of the time ($Z_\alpha=2.5$). (b) What cleaning conditions must be used to produce a compliance coal? (c) Are these cleaning conditions reasonable?

(a) Determination of $\hat{\mu}$.

It is assumed that the variability in the SO_2 emission parameter can be described by an AR(1) model and the Harrison County boiler has a heat rate of 10,000 Btu/kW-hr (10.55×10^6 J/kW-hr). To avoid an iterative solution, a nominal as-fired coal heating value of 12,500 Btu/lb (29,076 J/g) will be used to calculate the coal firing rate and reference lot size.

The nominal coal firing rate is:

$$\frac{10{,}000 \text{ Btu}}{\text{kW-hr}} \times 500{,}000 \text{ kW} \times \frac{1}{25 \times 10^6 \text{ Btu/ton}} = \begin{matrix} 200 \text{ tons/hr} \\ (181 \text{ Mg/hr}) \end{matrix}$$

In 24 hours, 4800 tons of coal is burned. The number of coal reference lots is:

$$n = \frac{\text{total coal burned over averaging time}}{\text{coal reference lot size}} = \frac{4800}{1200} = 4$$

The cleaned coal function of autocorrelation is calculated using Eq. 19-4:

$$\hat{\omega}_n(\hat{\rho}_1, n) = \left[\frac{1-\hat{\rho}_1^{\,2} - 2\hat{\rho}_1/n + 2\hat{\rho}_1^{\,n+1}/n}{(1-\hat{\rho}_1)^2}\right]^{\frac{1}{2}} =$$

$$\left[\frac{1-(0.5)^2 - 2(0.5)/4 + 2(0.5)^5/4}{(1-0.5)^2}\right]^{1/2} = 1.436$$

The value of $\hat{RSD}_n$ is:

$$\hat{RSD}_n = \frac{\hat{RSD}_1 \hat{\omega}_n}{\sqrt{n}} = \frac{0.10 \times 1.436}{\sqrt{4}} = 0.0718$$

Finally, the value of $\hat{\mu}$ is determined:

$$\hat{\mu} = \frac{E_L}{1 + Z_\alpha \hat{RSD}_n} = \frac{4.5}{1 + 2.5(0.0718)} = 3.82 \text{ lb } SO_2/10^6 \text{ Btu } (1642 \text{ ng } SO_2/J)$$

Note that the coal currently being produced by the Level 2 plant does not satisfy the estimated compliance requirements.

(b) Estimation of Cleaning Conditions

Estimates of the required cleaning conditions are made using Table 19-2. Note that the coal properties in Table 19-2 are given on a moisture-free basis and that the moisture-free and as-fired sulfur emission parameters differ in most cases by less than 1 percent.

(1) Assume crushing to 1-1/2 inch (37.5 mm) top size.

A linear interpolation of data in Table 19-2 can be performed to determine the float specific gravity required for a 3.8 lb $SO_2/10^6$ Btu (1634 ng SO_2/J) product.

The required float specific gravity is:

$$1.6 - \left[(1.6-1.4)\frac{(4.5-3.8)}{(4.5-3.6)}\right] = 1.44$$

It is difficult to control separating conditions to 1.44. After rounding down to 1.4 to ensure a satisfactory product, the properties of the cleaned coal are found from Table 19-2 to be:

Mean Emission Parameter = 3.6 lb $SO_2/10^6$ Btu (1548 ng SO_2/J)

Btu Recovery = 79.8 percent

Heat Content = 13,595 Btu/lb (31,622 J/g)

Ash Content = 6.0 percent

(ii) Crushing to 3/8-inch (9.5 mm) top size

An inspection of Table 19-2 shows that a 3.8 lb $SO_2/10^6$ Btu (1634 ng SO_2/J) product can be obtained at a float specific gravity between 1.9 and 1.6. The required float specific gravity is:

$$1.9 - \left[(1.9-1.6)\,\frac{(3.9-3.8)}{(3.9-3.6)}\right] = 1.8$$

The coal properties at this specific gravity are:

$$\text{Btu Recovery} = 97.7 - \left[(97.7-95.1)\,\frac{(1.9-1.8)}{(1.9-1.6)}\right] = 96.8$$

$$\text{Heat Content} = 13{,}375 - \left[(13{,}375-13{,}534)\,\frac{(1.9-1.8)}{(1.9-1.6)}\right] = 13{,}428 \text{ Btu/lb } (31{,}234 \text{ J/g})$$

$$\text{Ash Content} = 7.5 - \left[(7.5-6.4)\,\frac{(1.9-1.8)}{(1.9-1.6)}\right] = 7.1 \text{ percent}$$

(c) Reasonableness of Required Cleaning Conditions

Crushing to a top size of 1-1/2 inches (37.5 mm) and separating at 1.4 s.g. results in excessive coal energy losses. Crushing to 3/8-inch (9.5 mm) and separating at 1.8 s.g. provides a 96.8 percent Btu recovery. However, crushing to 3/8-inch (9.5 mm) may produce a large amount of fine coal and may result in high cleaning costs. Cleaning can probably be used to produce a compliance coal, but detailed plant design studies must be made to evaluate cost and performance trade-offs between the various coal top sizes and cleaning conditions which will provide a compliance coal. Studies must also be made on the feasibility of either modifying the existing Level 2 preparation plant or building a new plant. The use of alternative coals must also be considered.

Problem 2. The utility in problem 1 is evaluating coals from alternate sources to locate potential compliance fuels. A raw coal from the Pittsburgh Seam in West Virginia is available at an attractive price. The mean emission parameter of the coal is 3.8 lb $SO_2/10^6$ Btu (1364 ng SO_2/J). CSA data for 1200 ton (1088 Mg) reference lot sizes show that $\widehat{RSD}_1$=0.16 and $\hat{\rho}_1$ =0.25. Can this coal meet the conditions expected for a compliance fuel?

As in problem 1, four reference lots are to be fired during the averaging period. The raw coal function of autocorrelation is:

$$\hat{\omega}_n(0.25,4) = \left[\frac{1-(0.25)^2 - 2(0.25)/4 + 2(0.25)^5/4}{(1-0.25)^2}\right]^{\frac{1}{2}} = 1.202$$

The value of $\hat{RSD}_n$ is:

$$\hat{RSD}_n = \frac{0.16 \times 1.202}{\sqrt{4}} = 0.0962$$

Finally, the value of $\hat{\mu}$ is determined to be:

$$\hat{\mu} = \frac{4.5}{1 + 2.5\,(0.0962)} = 3.63 \text{ lb } SO_2/10^6 \text{ Btu} \quad (1561 \text{ ng } SO_2/J)$$

For these sampling conditions, the coal cannot be shown to meet the assumed compliance requirements. However, by increasing the coal sampling frequency (reducing the reference lot size) it is possible that this coal can be used as a compliance fuel. For example, assume that, at a reference lot size of 480 tons (435 Mg), it is found that $\hat{RSD}_1$=0.17 and $\hat{\rho}_1$ =0.35. The required value of $\hat{\mu}$ for these conditions at n =10 can be calculated to be:

$$\hat{\omega}_n(0.35, 10) = 1.383$$

$$\hat{RSD}_n = 0.0743$$

$$\hat{\mu} = 3.80 \text{ lb } SO_2/10^6 \text{ Btu} \quad (1634 \text{ ng } SO_2/J)$$

For this sampling frequency the raw West Virginia coal is seen to meet the assumed compliance requirements.

Practical Considerations. This chapter has considered the use and limitations of coal cleaning as a technology for complying with SO_2 emission regulations. However, selection of the least cost option for complying with an SO_2 emission regulation at a given site is complex. Many different coals can be used. Blending of low and high sulfur coals, either cleaned or uncleaned, can also be considered. The use of flue gas desulfurization or other SO_2 emission reduction technologies is also possible. The final choice will depend upon a careful consideration of all options, taking the major site-specific design factors into account. Once the number of options has been narrowed, preliminary design, performance, and cost studies can be conducted to develop information on which investment decisions can be made. Within this overall context, an evaluation of coal washability data and potential preparation plant costs is a necessary first step in evaluating the coal cleaning options. Information in this chapter should aid in selection of appropriate technologies for air pollution control.

Table of Conversion Factors

Multiply English Unit	by	To Obtain SI Unit
pound (lb)	453.59	gram (g)
ton (2000 lb)	0.907	megagram (Mg) = metric tonne
inch (in.)	0.0254	meter (m)
foot (ft)	3.048	meter (m)
British Thermal Unit (Btu)	1054.88	Joule (J)
Btu/lb	2.326	J/g
lb/10^6 Btu	429.907	ng/J
$/ton	1.1025	$/Mg
$/$10^6$ Btu	0.9480	mill/MJ = 10^{-3} $/MJ
lb/ft^3	0.0160	g/cm^3

Tyler Screen Size Mesh Openings

Mesh Size	Sieve Opening in.	mm
14	0.0469	1.18
28	0.0234	0.60
48	0.0117	0.30
100	0.0059	0.15
200	0.0029	0.075
270	0.0021	0.053
325	0.0017	0.045

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